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THE IMPACT OF MANPOWER REQUIREMENTS AND PERSONNEL RESOURCES DATA ON SYSTEM DESIGN

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FOREWORD

This study was initiated by the Personnel and Training Requirements Branch, Training Research Division, Aerospace Medical Research Laboratories, Wright-Patterson Air Force Base, Ohio, under Project 1710, "Human Factors in the Design of Training Systems," Task 171006, "Personnel, Training, and Manning Factors in the Conception and Design of Aerospace Systems." The research was accomplished by the System Effectiveness Laboratory, The Bunker-Ramo Corporation, Canoga Park, California, under Contract No. F33615-67-C-1650. Dr. David Meister was principal investigator, assisted by Mr. Dennis J. Sullivan. Dr. William B. Askren was the investigator for the Aerospace Medical Research Laboratories. The research sponsored by this contract was started on 1 June 1967 and was completed on 31 May 1968.

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This technical report has been reviewed and is approved.

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ABSTRACT

The major purpose of this study was to determine the effect on system design of using manpower and personnel resources data as design requirements. Secondary objectives were to determine under what conditions and in what form these data should be used to have maximum effect on design. Equipment, manpower data (e.g., quantities and skill levels), and personnel resources data (PRD) inputs (e.g., task information) which were produced during the development of the Titan III propellant transfer and pressurization subsystem were adopted and presented incrementally to six design engineers to simulate the Air Force phase 1A/1B development of that subsystem. Subjects were required to create schematics, equipment descriptions and drawings, control panel layouts, operating procedures and bills of material. Cost-effectiveness measures including equipment cost, equipment reliability, human reliability, system safety and design adequacy were applied to the data. It was found that manpower requirements and PRD inputs do influence the equipment configuration, but in this study only moderately, because the equipment design proceeded so rapidly that incremental PRD inputs inevitably lagged the design. Engineers were responsive only to inputs which are framed as design requirements and which were interpreted in design-relevant terms. Confirming the results of previous studies, engineers were found to be generally unaware of or indifferent to personnel considerations. Different engineers interpreted the same design requirements and assigned priority to design criteria differently. The engineers relied heavily on experience and stereotyped solutions for design answers. The results of the study indicate that, if manpower and personnel resources data are to be incorporated into design, it is necessary to supply these inputs to the engineer as design requirements in his initial statement of work. Consequently, fundamental manpower and personnel analyses must be performed prior to the issuance of a Request for Proposal (RFP) and not delegated to the development contractor. The contractor must be required to design to a detailed manning structure which is specified in his statement of work. Further recommendations are supplied which suggest ways in which Air Force management of the personnel subsystem program should be revised.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF TABLES

LIST OF ILLUSTRATIONS

GLOSSARY

Air Force Specialty (AFS)

A grouping of duties and tasks related in skill, knowledge, difficulty, operational sequence, and the like, and making up a job or specialty.

Design Input Tests (DIT)

Design Input Tests require the subject to analyze an individual input directly rather than integrate the input into an overall design as required in the DPT. (Sessions 9-10 of the present test series were modeled after the DIT.)

Design Product Tests (DPT)

Design Product Tests in which the solutions to the problem was the actual completion of the design task; the actual designing of a system to satisfy the problem inputs or requirements. This type of test examines design "longitudinally," that is, the entire process from assignment of the problem to its completion. (The first eight sessions of the experimental portion of this study were modeled after the DPT type of situation.)

Personnel Equipment Data (PED)

An element of the Personnel Subsystem which is made up of the analytical data, in the form of task and equipment information that describes the nature and interrelationships of functions performed by system personnel and system hardware.

Personnel Resources Data (PRD)

Personnel Resources Data is defined as the data which implements or interprets a specific personnel requirement.

Qualitative and Quantitative Personnel Requirements Information (QQPRI)

QQPRI is composed of data describing the quantitative requirements, qualitative requirements, training requirements and prerequisites for the personnel required to operate, maintain, and command a given system. This data are used in planning for system personnel, training and manpower.

Requirements Allocation Sheets (RAS)

Requirements Allocation Sheets (RAS) are a form of system design documentation upon which are identified the design requirements for specific operations, maintenance, test and activation functions.

SECTION I

INTRODUCTION

A. NATURE OF THE PROBLEM

The Importance of Human Factors in System Design

The importance of human factors to system performance has been shown a number of times. Both logically and empirically, the negative effect of inadequate consideration of the human element during design can be demonstrated The contribution of human error to the unreliability of overall system performance has been graphically illustrated by Meister and Rabideau (1965, Figure 1-1) and empirically by Meister (1967). In the latter study, approximately 24% of overall system unreliability could be attributed to the effect of human error. In 1960, Shapero et al. reported on a survey of several major missile systems and reported that the percentage of equipment failures caused by human error ranged from 20% to 53% of the total failures reported. Willis (1962) estimates "that 40% of the problems uncovered in missile testing derive from the human element. 63.6% of the (shipboard) collisions, flooding and grounding could be blamed upon human error. Reports produced by the United States Air Force indicate that human error was responsible for 234 of 313 aircraft accidents during 1961" (p. 1).

A second area of concern is that of the cost of the system, which is defined today in terms of life-cycle costs. The evidence is accumulating that the cost of the personnel to operate and maintain a system throughout its useful life is equal to or exceeds those of the hardware. Thus, we have a double-edged problem, performance decrement and high costs, which can be related to the human element of the system.

This problem has been made more severe by a history of development of new systems with emphasis primarily on the design of hardware and with little or no regard for the capability or cost of the personnel that will be available to support the system. It has been advocated that one way to reduce the problem is to develop systems with human factors data included as design requirements. To this end, the Air Force put into practice 10 years ago what has come to be known as the Personnel Subsystem Concept. The Personnel Subsystem is defined (AFR 30-8, USAF, n.d.) as "that major functional part of a system which, through effective implementation of its various elements, provides the human performance necessary to operate, maintain and control the system and its intended operational environment."

"The major objectives of the Personnel Subsystem program are: (a) to promote the acquisition of functionally integrated systems and facilities which can be safely and reliably operated, maintained, and supported by USAF personnel; (b) to provide appropriate agencies with timely planning and technical information concerning personnel, training, and life support requirements which systems will impose on the Air Force structure; and (c) to insure timely development and acquisition of training equipment, facilities, and protective equipment for the support of system personnel. To accomplish these objectives, the PS effort embraces virtually all the considerations of man in the system, whether these involve the application of human engineering principles to the design of the operational hardware, the selection and development of training equipment, or the preparation of informational job aids intended to assist personnel in carrying out their assigned tasks." (AFSCM 80-3, USAF, 1963)

Despite this, and despite very intensive missionary efforts by human factors specialists and governmental managers, it is almost a truism that human factors specialists, working on system development projects, experience grave difficulty in making effective inputs to that development. Thus system failures resulting from human error continue high and system manpower costs continue to grow at an accelerating rate. Why do these conditions continue to exist? The answer is obvious to those experienced with the system development process. It is the fact that human factors specialists are brought in late to system development projects after basic design concepts are developed, concepts which reflect only superficially any consideration of personnel factors. Thus the human factors data which should be incorporated in system design to achieve an optimal, more cost/effective system are too late to have an impact on design. To make matters worse, many of these human factors inputs are regarded by design engineers as so much paper work and rejected out of hand. The lowest priority in design analysis is given to criteria dealing with personnel aspects. (This is not to say that human factors data are completely ignored; they play a role obviously in such PS aspects as the development of training curricula.)

All of these conditions routinely exist in almost every system development project (except those fortunate few like the NASA man in-space flight program) despite very large sums of money expended for proper implementation of the personnel subsystem.

What can be done to improve the situation? The answer can only be determined by an examination of the design/development process itself and by an evaluation of the usefulness of the various human

factors data and analyses to that process. Those data and analyses which are ineffective should be discarded; those which are only marginally effective should be modified to improve their utility; those which appear to have the greatest potential for influencing design should be emphasized.

This study is, therefore, directed toward a controlled examination of the utility of PRD in system design and to the determination of the conditions under which PRD can be effective in influencing that design.

Manpower Requirements and Personnel Resources Data

The data and analyses selected as the focus of this study were those descriptive of the quantity and skill capability of the personnel required for a system. Rationally, it seemed that these kinds of inputs used as design requirements could have an effect on the system configuration. These data have been termed Manpower Requirements (MR) and Personnel Resources Data (PRD). MR were defined as those data which prescribe the quantity and quality of personnel comprising the crew, and PRD were defined as that information which implemented or interpreted the Manpower Requirements for the designer, e.g., list of tasks, task time capability, task human error rate probability. Table III, page 26, further describes these data.

It was assumed that manpower requirements can be quantitatively and precisely derived from early analysis of mission/system requirements, before equipment development begins. Hence, manpower requirements with their supportive personnel resources data can be made available to the design engineer at the same time he begins design of the system.

The Potential Effect of Manpower Data Upon System Design Can Be Logically Demonstrated

If the number of personnel available to crew a subsystem under development is increased or decreased by a factor of 2, it seems reasonable that the subsystem design would be substantially modified to accommodate the change in personnel. The same should apply to a change in skill level, as between highly trained, well experienced personnel and apprentices who have received only basic training.

Can this effect be empirically demonstrated, however? Does the designer react to the imposition of a manpower requirement by a change in design which reflects at the very least his attempt to satisfy that requirement? One of the goals of the study was to

determine the conditions under which manpower requirements (apart from its implementation data) can most influence the subsystem configuration.

It is possible, for example, that the consequences of such requirements are not sufficiently apparent to the system designer. If one were to specify that for one design all operators will be approximately 6 feet 4 inches in height, and for another the maximum operator height will be 3-1/2 feet, it is apparent that equipment configuration will be materially affected (or if it is not affected, performance decrement will be high). Indeed, where requirements are so extreme, it is likely that the designer will not need the prompting of the human factors specialist to cause him to include those requirements in his design.

But how does the designer cope with a manpower requirement that he design for a subsystem which will be operated and maintained by personnel between the 5th and 95th percentiles (e.g., personnel with three- and five-level skill designations)?

PRD as Communicated Information

Before exploring the potential reasons for the lack of effectiveness of PRD in influencing design, it is necessary to place the former in a conceptual framework. PRD inputs are communicated information. Hence the format in which that information is communicated, its timing relative to other events in the developmental process, the number of other inputs with which it competes and its clarity to the recipient of the information (the design engineer) will all affect the acceptance of the message and its utility to the designer. No matter how intrinsically meaningful the data presented, if those data are difficult to interpret in design terms, or are presented at the incorrect time, etc., the effectiveness of the data will be reduced.

Reasons for Ineffective PRD

Assuming, therefore, that personnel requirements have the capability of influencing hardware design, the possible reasons why the PRD inputs implementing these requirements fail to produce the desired impact fall into the following categories:

(1) Inappropriate Timing. Many PRD inputs tend to lag significant design decisions rather than to anticipate them. In fact, even to be concurrent with these decisions is to be too late. The average human factors specialist, who often lacks all but a minimal engineering background--if that--finds himself heavily dependent upon the flow of engineering information to him as the basis for his contributions to design. Consequently, he fails to participate in the preparatory work which results in terminal design decisions. However, it is precisely in this preparatory phase that fundamental decisions are made which become extremely difficult to reverse.

Attention must also be directed to the relatively informal character of the analyses leading to basic design decisions. Formal paper work tends merely to describe decisions that have already been made informally. The utility of formal PRD inputs (as differentiated from informal directly expressed verbal inputs), therefore, tends to be reduced. If formal inputs are made, they must be made in advance of the formal decisions or they will not be considered.

The implications of inappropriate timing should, it was felt, be one of the factors examined in the proposed study. If the utility to the designer of the PRD input can be significantly improved by improving its timing relative to major system development milestone, then appropriate solutions to this problem could be recommended.

(2) Inadequately Expressed Implications. It must be presumed that each human factors datum has some implications for the design configuration; but in many, if not most, PRD inputs, these implications are not expressed. It is, for example, no use to tell the system designer merely that the personnel who will man his system will have a five-level skill. It is necessary to tell him, in addition, what this datum implies for his design or what he should do in concrete equipment terms to account for that skill level. Without this additional information, the design engineer is lost. It is, therefore, a reasonable hypothesis that the utility and acceptability of PRD inputs would be much increased if greater attention were paid to describing the design consequences of PRD.

(3) Inappropriate Designer Attitudes. The whole problem is complicated by the fact that, according to the results of previous studies of human factors information utilization by designers (Meister and Farr, 1966, Meister and Sullivan, 1967), designers accord behavioral inputs a rather low priority in the

scheme of things. (The studies cited, which have significant interrelationships with the present one, will be discussed in some detail later.) Although he would--and does--protest the contrary, the designer has an acquired bias against PRD inputs, and thus the clarity of the information presented must be intensified if it is to breach this barrier. These difficulties are intensified because system development is often chaotic and characteristically behind schedule. The designer is beset with a host of data inputs, each competing with the other; hence, the human factors message must be louder than would otherwise be required if it is to receive a hearing.

Factors to be Examined

It is apparent, therefore, that in any investigation of the effectiveness with which manpower requirements and personnel resources data inputs are utilized in system development, the following factors must be examined:

(1) The manner in which the engineer ordinarily designs, because PRD inputs must fit into that process;

(2) The format or manner in which PRD inputs are supplied to design engineers;

(3) The timing or sequence with which PRD inputs are provided;

(4) The design-relevancy of the data supplied in PRD inputs;

(5) The effect of manpower requirements as requirements on hardware design concepts;

(6) The availability of information as a whole to the engineer during the design process;

(7) The engineer's attitude toward the personnel aspects of the system and to human factors data as inputs to design.

B. PREVIOUS RELEVANT RESEARCH

Research Relevancy

A discussion of all the research which has been published on the general subject of manpower, personnel requirements and PRD is beyond the scope of this report and would in any event be irrelevant to the questions raised in Section A. (For those interested in a general review of the available literature, it is suggested that they read the following reports: Powell (1963), Hannah (1965).

The irrelevancy of most of this literature results from the unfortunate fact that, although great attention has been paid to the mechanics of PRD development, research on PRD usefulness, particularly to the design engineer, is practically nil.

With the exception of two studies performed by Meister and Farr (1966) and Meister and Sullivan (1967), which will be discussed in detail below, research has not addressed itself to the practical utility and effectiveness of human factors inputs within the design process. It is--or should be--characteristic of any empirical discipline that its techniques, data and theories are constantly under examination and revision to bring them into accord with reality. Human factors inputs should also be subjected to the same kind of reality-testing. Unfortunately, however, with the exception of the two studies cited above, there has been very little, if any, validation of human factors tools.

There are two reasons for examining these studies in some detail. First, because the general research strategy employed in these studies was also used in the present investigation. Second, the results achieved in the present study are much more understandable if viewed in the light of the previous research.

Previous Research Goals

The specific goals of the two studies which are relevant to the present investigation were to answer the following questions:

(1) What kind of information does the designer use as the basis of his design decisions and what kinds of analyses does he make of design problems?

(2) How efficiently does the designer utilize particular human factors inputs and what design implications does he draw from these inputs?

(3) In what form will these inputs have their greatest effect?

(4) What are the design engineer's attitudes toward human factors personnel, human factors information and the role of the operator in design?

(5) To what extent does he routinely include human factors in his design analyses?

In contrast to the present research, the two studies dealt with human engineering data inputs of the "knobs and dials" type, that is, those inputs which are most directly relevant to the characteristics of the equipment.

Research Strategy

The general philosophy underlying the approach in these studies assumes the following:

How engineers analyze their design problems determines how they use human factors information and the manner in which operator considerations are incorporated into design. In other words, information has value to the engineer only to the extent that he can relate it to his design task.

Consequently, in order to secure data about the usefulness of human factors inputs to design, it is necessary to place the engineer in a situation which requires him to design and in which the inputs provided can be (if useful) related to the design task.

Thus, it is no good asking designers to verbalize their design methodology, to ask them, baldly, how do you go about designing? Much of their methodology is covert; the engineer may even be unaware of the essential creative processes he employs. In addition, the engineer is not overly verbal.

Consequently, a formal interview/questionnaire methodology was rejected, as well as any technique which was not based on, or could not be incorporated into, concrete design situations. The method followed was, therefore, to (1) present the engineer with a series of realistic design problems (representative of those he ordinarily encountered), (2) provide him with informational inputs related to these problems, (3) require him to solve the problems, (4) observe how (or if) he used the inputs in the problem solution, (5) and then, following problem solution, review with the engineer how he achieved that solution and the value of the inputs provided.

Types of Test Situations

Two types of test situations were developed. The rationale for these test situations was as follows:

Any individual design problem will (if it is to be realistic) require only a limited number and type of human factors inputs. Thus, for example, a console design may require consideration of anthropometric requirements but not communications; or consideration of meter sizes, but not maintenance test points. Consequently, it is impracticable to develop a complete range of fully articulated design problems in any one test situation.

The two types of design tests developed were:

(1) The Design Product Test (DPT), in which the design solution or product was the actual layout of an equipment to satisfy the problem inputs or requirements. This situation studied design "longitudinally," that is, the entire process from assignment of the problem to its completion. (Parts of the experimental methodology of the present research were modeled after the DPT type of situation.)

For example, one DPT required the layout of a command/control station aboard a missile frigate. Another required the sketch of a self-contained portable test set for circuit modules (printed circuit cards). Design requirements for these equipments were described in terms of a design specification format commonly used in Department of Defense military procurement, e.g., applicable specifications, performance, operability, reliability and maintainability requirements, use of standard and commercial parts, etc.

The design required for the DPT was that of a "conceptual sketch," something between an artist's rendering and a fully detailed design. Such a drawing is often made for an initial design analysis such as might be required in responding to a Request for Proposal or in the very early stages of conceptual system definition.

(2) The Design Input Test (DIT), in which an equipment layout was not required of the designer, but in which he had to analyze the individual input directly. These "cross sectional" situations particularly emphasized the analytic inferences to be drawn from the design problem. (Another part of the experimental methodology of the present study was modeled after the DIT.)

As an example of a DIT test item, the designer might be presented with the problem of designing a shipboard equipment and asked to list the human engineering inputs he would need to solve the problem. DIT situations were necessarily somewhat more abstract than those of the DPT, because they dealt with methodology that would or should be adopted, rather than the completed product of that methodology, i.e., a drawing.

The difference between these two test situations was one of degree only; in each case a design problem was explicitly or implicitly presented, but in the first the focus of interest was the design output, whereas in the second interest lay in the designer's direct response to input characteristics.

It is important to note that the tests were so developed that they demanded analysis of operator factors if the designs were to be optimal. In other words, the production of responses involving analysis of operator considerations was not merely incidental to these designs, but were an integral requirement. For example, the design specification for DPT I required that a decision be made between single vs. multi-operator use of the equipment, a decision which would have significant implications for design.

It was essential that these test problems be highly realistic, since designers tend to react negatively to situations in which technical details are incorrect or inappropriate. To ensure the necessary degree of realism, highly experienced senior design personnel reviewed the tests and made any required modifications before the tests were presented to subjects. (This procedure was followed in the present study as well.)

Test Atmosphere

Each test required 4 hours (a pretest had indicated that this length of time was sufficient to elicit the desired responses), and there was a week's hiatus between each test. The tests were administered individually.

A highly informal atmosphere was encouraged. During the DPT test period, the designer was entirely free to respond as he wished, even to the point of leaving the test area if he wished. He had available to him a standard drawing board, drawing equipment, copies of all military specifications noted as applicable in the design problem statement, as well as other human factors, reliability and maintainability handbooks which are considered "standard" texts in these fields. The designer was informed that he would be observed during the session, but that he was free either to ignore the observer or to interact with him as he wished. A tape recorder was provided to record the designer's verbal responses.

During the DIT, the investigator interacted directly with the subject, and the test items can be considered as a specialized type of interview schedule. DIT responses were recorded primarily on tape recorder with some written responses required (where lists of alternative responses had to be ranked). Because of the unstructured nature of the interview probes, the test situations can be considered as having an almost clinical atmosphere.

The debriefing following the engineer's completion of the design and during the DIT was extremely "loose." Although a series of standard questions was asked by the investigator[1], the subject's responses were followed up to secure greater detail, so that in effect the engineer determined where the discussion led. At the same time, the investigator did not content himself with the initial response to a question, but continued to probe intensively, requiring the subject to explain his answers in more detail, until the subject's ability to respond was exhausted. This procedure was followed to get beyond any relatively stereotyped response patterns the engineer might have. Discussions were sufficiently probing that a few subjects became somewhat emotional in their replies.

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[1] Sample questions included:

(1) Did the specification contain enough information for you to design what you would consider a satisfactory control panel?

(2) Did it lack any information that you felt you needed? If so, what was lacking?

(3) What would you consider to be the major problems you had in designing this equipment?

(4) What factors (design parameters) did you consider most important in designing this equipment?

These questions were considered only as models. The investigator was free to modify them in terms of the sequence and content of the subject's responses. In particular, the subject was asked to explain each design behavior observed. Emphasis was placed on the reason why a particular design action was taken. (Example: I see that you located this bank of toggle switches at the extreme lower left of your control panel. Can you tell me why you located them in that position?)

The same procedures were employed in the present test series.

Subjects

Subjects in the first study (Meister and Farr, 1966) were 20 design engineers, including three design managers (differentiated from their colleagues by greater breadth of experience and responsibility). These subjects were selected from the Product Design and Services Department of The Bunker-Ramo Corporation (BRC). This is the department whose design responsibilities would ordinarily involve human factors considerations most heavily, since these responsibilities include the design of control panels, the external chassis of the equipment, the packaging of the total equipment for maintainability, etc. The engineering responsibilities these subjects had were largely confined to detail design; in other words, although they made design decisions, these decisions were on a detail level.

The subjects selected were those who had had a reasonable amount of experience in actually designing equipment. Draftsmen and junior engineers, who had responsibility for providing only the details of a drawing after the basic concept had been provided by others, were excluded.

The median amount of subject experience was 14 years. However, only half of the subjects had a bachelor's degree in engineering or the equivalent in course credits.

Subjects in the second study (Meister and Sullivan, 1967) were 10 design engineers from the McDonnell-Douglas Aircraft (DAC) Division. Their range of specialization was substantially broader than the BRC subjects, including crew accommodations, cockpit design, controls and displays, escape systems, life support systems, interiors, etc.

These subjects represented a more sophisticated and experienced population than the BRC group; this sophistication and experience were reflected in their responses to the design problems.

Median years of experience were 15, about the same as the BRC group. However, all but two of the DAC subjects had their engineering degrees, whereas only half of the BRC sample had degrees or their equivalent. All of the DAC subjects were what one could categorize as "lead engineers."

In summary, therefore, 30 design engineers, with varied experience and education working in two industrial environments, were tested on a variety of human engineering inputs for a total of approximately 360 hours.

Findings

The principal findings of the two studies which are relevant to the present investigation can be summarized as follows:

(1) Design engineers have little or no interest in human factors and characteristically fail to employ human factors criteria in their designs.

(2) Design analysis is largely determined by constraints and experimental stereotypes.

(3) The most important source of information for the designer is the design specification (statement of work).

(4) The designer makes little or no use of human factors information.

(5) Human factors information is considered by the design engineer as lacking applicability to specific design problems.

C. PURPOSE OF THE PRESENT STUDY

The present study was conducted to determine the effect on system design of using manpower and personnel resources data as design requirements and to determine under what conditions these inputs can be made to have maximum influence on system configuration. One might suppose after reading the largely negative results of the two previous studies that no further investigation of the effectiveness of human factors inputs need be performed. But, in fact, these studies documented only what is generally accepted by human factors specialists who are in a position to observe the use to which their recommendations are put.

Therefore, as was pointed out in sub-section A (Nature of the Problem), it is necessary to find out why human factors inputs are not effective in system design and under what conditions they can be made effective. The inputs provided to the design engineer in the previous studies were limited to handbook-type data. There are, moreoever, a number of distinctions between the previous studies:(1) the inputs provided to the design engineer in the previous studies were limited to handbook-type data and did not reflect manpower requirements which ought, on a purely logical basis, to be considerably more relevant to the design of the system; (2) the inputs used as test material in the previous studies were those which would ordinarily be supplied in the later phases of detail design, after fundamental design decisions had been made. Hence, one would expect them to have less influence on design than PRD inputs which should be applicable to the initial design concept; (3) the effectiveness of the human engineering inputs used in the previous studies were

not related to the chronological sequencing of system development, hence it was impossible to determine at what stage of that development these inputs could be effective.

Thus, the primary objectives of the present study, stated in question form were:

(1) Do differences in manpower requirements (MR) influence subsystem configuration?

(2) Do personnel resources data (PRD) inputs have a significant effect on equipment design?

(3) At what stage of subsystem development do MR and PRD inputs have their greatest impact on equipment design?

(4) In what forms are PRD inputs most effectively used by designers?

Secondary questions necessary for a better understanding of the design process were:

(5) What is the design engineer's concept of human factors in system design, and his attitude toward PRD inputs?

(6) How does the manner in which the engineer designs affect the utilization of PRD inputs?

(7) How available is information as a whole to the engineer during design?

SECTION II

TEST METHODOLOGY

A. GENERAL STRATEGY

The research strategy developed by Meister and Farr (1966) and Meister and Sullivan (1967) involves placing the engineer in a realistic design situation in which he must solve a series of design problems by using informational inputs related to these problems. In adapting this general methodology to the present study, the following steps were performed:

(1) Selection of an already operational subsystem which could serve as a model subsystem for the development of test inputs.

(2) Selection of appropriate engineer-subjects skilled in design of the type of subsystem selected.

(3) Determination of the equipment and PRD inputs which are characteristically provided during the system definition phase of development.

(4) Development of manpower and personnel resources data inputs.

(5) Determination of the sequence in which these inputs should be provided.

(6) Determination of the design responses and outputs which the engineer-subjects should supply in attempting to solve the design problems.

(7) Determination of specific measures which could be used to answer the questions which initiated the study. (See Experimental Design, page 39).

B. DEVELOPMENT OF THE EXPERIMENTAL SITUATION

1. Selection of the Test Subsystem

The initial step in the development of the experimental situation was the selection of an already operational subsystem which could be used as a model for the development of experimental inputs and required design outputs. Since one of the goals of the study was to determine at what stage PRD inputs were most effective, and since

PRD inputs are supplied progressively during system development, it was necessary to simulate the progressive development of a subsystem. As the time available for testing was limited, the subsystem level was the most complex which could be handled reasonably in the time available. The subsystem level was also selected as requiring a greater variety of inputs and design outputs than the development of any single equipment, no matter how complex.

The original motivation for using an already operational subsystem as a model was to permit the comparison of the experimental subsystem designs developed by subjects with the original subsystem design. It was hypothesized that if the experimental subsystem was developed with the aid of PRD inputs, the resultant design would be superior to the one originally developed. This, in turn, would demonstrate the usefulness of PRD inputs.

Differences Between the Original and Test Subsystem.

During the development of the test materials, however, it was found that the conditions under which the original subsystem was designed were found to be sufficiently different from those under which the experimental subsystem was designed so that any comparison of this type would be hopelessly contaminated. Among the differences in design conditions between the original and experimental subsystems were the following:

(1) The test period during which subjects developed the experimental subsystem was highly compressed in time (i.e., three months) relative to the original development. (Obviously, sincetest time was not unlimited.)

(2) The original subsystem design was the product of a large number of interacting design engineers, some of whom worked only on minor phases of the design, whereas in the experimental situation each subject performed a complete independent design. The reason for the latter was to secure a sufficient number of independent designs to test the effect of the experimental variables. Had all subjects worked together on the design problem, only one subsystem would have been available for analysis.

(3) Although cost and schedule constraints were undoubted factors affecting the original subsystem design. these parameters could not realistically be included in the experimental situation. Schedule was irrelevant to this study, and subjects were merely asked to minimize cost commensurate with safety.

(4) To maintain experimental control, the experimental situation had to be orderly and progressive, whereas actual design is ordinarily harassed by many perturbations.

(5) The state of the engineering art in propellant transfer design had progressed between the time the original subsystem was designed and the experimental subsystem was begun; consequently, differences in selection of components and design concept would undoubtedly be found.

For all of these reasons, the concept of comparing the original subsystem design with the experimental subsystem was impossible to achieve; any such comparison, since it was uncontrolled, would have been like comparing apples and oranges.[2]

However, the ideal of using an already operational subsystem as a model was an excellent one, for several reasons:

(1) Both equipment and PRD inputs, the details of which would otherwise be difficult to create if one had to create them out of imagination, could be abstracted from the original documentation.

(2) The amount of informational detail that should be provided at the various stages of the experimental subsystem development could be determined from the original documentation.

(3) The face validity (i.e., realism) of the inputs could be assured because they were produced in the original subsystem design.

(4) The design responses required of subjects could be determined on the basis of the design outputs developed in the original subsystem.

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2. These differences, however, should not lead the reader to assume that they invalidated the experimental situation as a tool for studying the design process. The essence of that process--which is the presentation of realistic problems and realistic inputs--was included in the experimental simulation. All subjects were impressed with the realism of the test atmosphere, especially since the testing was conducted in their own plant and practically at their own desks.

Criteria for Selecting the Operational Subsystem

The criteria for selection of the model subsystem were as follows:

(1) The subsystem should be one to which personnel functioning is important. Obviously, the selection of a subsystem which was so automated as to require few personnel functions would not enable the investigators to provide PRD inputs that could be meaningfully related to the design problem.

(2) The subsystem should be one which involved both operator and maintenance functions. This would permit the analysis of the effect of inputs related to both types of functions. If a subsystem was selected that was completely operator or completely maintenance-oriented, the conclusions derived would be limited.

(3) The subsystem should have an appropriate degree of complexity. Overly simple subsystems should be avoided since the number of PRD inputs and their effect on subsystem design would be minimal. At the same time an overly complex subsystem would have made it difficult to supply the necessary subsystem inputs within the time schedule established. A subsystem requiring the services of between five and ten personnel was seen as the ideal size.

(4) The subsystem should be one whose development proceeded in accordance with AFSCM 375-5 (USAF, 1964) or whose materials could be so modified that they fit into the context of the 375 system engineering approach. AFSCM 375-5 is utilized as a framework for the development of the experimental PRD inputs because Air Force systems are required to be developed in the spirit, if not to the letter, of AFSCM 375-5. The historical records of subsystem development should be complete enough to minimize the development of new material (as opposed to editing or revision of old material).

The Subsystem Selected

With these criteria in mind, several alternative subsystems were considered and evaluated before the investigators selected the model subsystem.

The subsystem selected was the Propellant Transfer and Pressurization Subsystem (PTPS) for the Titan III Space Launch system. For those not familiar with missile technology, the Titan III PTPS is a large scale bi-propellant transfer subsystem used to support a fixed base, two-stage booster for scientific payloads. This subsystem is responsible for receiving propellants from railroad cars, for storing propellants in Ready Storage Vessels (RSV) for a period of up to 30 days, and for transferring the stored propellants to the booster tanks. The propellant consists of a mixture of nitrogen tetroxide as oxidizer and unsymmetrical dimethylhydrazine and hydrazine, highly volatile and extremely toxic either individually or in combination, automatically imposing the most stringent safety provisions. Additional material describing this subsystem can be found in Appendix I, PTPS statement of work.

2. Selection of Subjects

Characteristics. The six engineers who made up the subject population for this study were selected from the Test Engineering Department of The Marquardt Corporation (TMC), Van Nuys, California. Engineers were selected from this company because the use of the Titan III propellant transfer subsystem as the model for the experimental design required the selection of personnel skilled in the design of propellant transfer subsystems.

The organizational structure within which these subjects functioned made a particularly unique group for use in a micro-simulation of the design process. Each of the subjects had been and was at the time of testing charged with the responsibility for the complete design of propellant subsystems. This included such major developmental stages as definition of initial system requirements, development of fundamental design concepts, definition of the equipment configuration, costing the system design, writing of operating procedures, and test and operation of the prototype system. Consequently, they had had extensive experience with all of the phases of system development with which this study was concerned.

Sophistication. In comparison with the subjects utilized in the previous two studies reviewed in Section I, the engineers in the present study can be considered the most sophisticated. If one defines a system engineer as one who must be concerned with all aspects of the system under development, they were true system engineers. Moreover, they had a much greater feel for the actual molecular design, installation and operation of hardware than the usual system engineer who ordinarily concludes his work at the "paper-work" stage.

During the test sessions, the investigators found the engineers to be an unusually qualified population with regard to the type of subsystem they were accustomed to design and the problems involved in the operation of these subsystems.

One might ask, then, in advance of the study results: Might their very sophistication make these subjects non-representative?

In actual subsystem development only highly qualified system engineers are permitted to make fundamental design decisions. True, the investigators might have selected a less experienced subject population; however, the study results might then have been attacked as possibly resulting from subject unfamiliarity with these design problems.

In one respect, however, the engineer-subjects of the present study may be considered atypical, perhaps. Because of the extreme hazard involved in the type of systems with which they were concerned, they were particularly sensitive to the safety aspects of the system. They, therefore, considered human factors in their design from the standpoint of avoiding situations which could be hazardous to life.

An analysis of the education and experience background of TMC subjects is presented in Table I. The two experimental groups described subsequently were equated on the basis of number of years of experience.

Once recovered from their initial reserve and wariness in the face of an unfamiliar experience, all subjects were extremely co-operative and displayed great interest in the pursuit of the study.

3. Determination of Equipment Inputs

In addition to PRD inputs, equipment inputs were provided to serve as the context for the PRD inputs as well as the information base for the design. These included the following:

(1) Statement of work which initiated subsystem development.

(2) System and equipment functional flow diagrams (at progressive levels of detail).

(3) Requirements Allocation Sheets (RAS).

(4) Descriptions of equipment characteristics.

(5) Maintenance analyses

TABLE I

SUBJECT EDUCATION AND EXPERIENCE

Subject	Education	Years of Experience
K	BSME	12
J	3-1/2 rs. (M.E.)	15
D	BSCE	15
S	2 years (M.E.)	12
H	BSME	26
N	BSME	24
		17.3 Mean

To develop the equipment inputs, documentation produced during the development of the Titan III PTPS was examined, courtesy of the Martin-Denver and Ralph M. Parsons Companies, and pertinent material extracted. The basic data sources reviewed are listed in Table IV. To ensure technical accuracy and completeness of the equipment inputs provided to the subjects, they were reviewed by the Chief Design Engineer of The Marquardt Corporation, and required revisions were incorporated.

All inputs were provided in complete form except where it was desired that the subject solve a problem which required him to develop or complete some part of the input. For example, if system functions on Requirements Allocation Sheets were to be analyzed by the subject to determine appropriate equipment characteristics, all necessary data were included on the sheets except for those dealing with the equipment characteristics. Complete inputs were provided because the designers were not expected to be able to develop all the documentation which would ordinarily be developed due to the time-scale involved in the simulation. Moreover, all PRD inputs were presented in toto, since designers do not ordinarily develop such inputs and do not have the experience needed to do so. In addition, it was the designer's response to the PRD inputs as reflected in his design outputs which was of interest.

Input Presentation Ground Rules

The following ground rules were followed:

(1) Each PRD input was supplied, along with an engineering input which required some analysis, decision or drawing. It was assumed that the engineer ordinarily would not analyze PRD inputs, except in terms of some system development requirement which involved the use of that PRD input.

(2) All inputs to subjects were supplied in written form, except where immediate circumstances (e.g., answers to questions asked by the subject during the test session) made this impossible. Any input provided orally was documented immediately following its transmission.

(3) Instructions to subjects were provided verbally, but they were allowed to read the same instructions in written form; and those written instructions were available to him throughout the test session.

TABLE II

SYSTEM DEVELOPMENT ACTIVITIES
AND
PERSONNEL INPUTS

	CONCEPTUAL				DEFINITION			ACQUISITION
SUB-PHASES or STAGES	HQ. PLANNING STAGE →	SYSTEM CONCEPT STAGE →	SYSTEM FEASIBILITY STAGE →	CONCEPTUAL TRANSITION STAGE	A → SPO PLANNING	B → CONTRACTOR DEFINITION	C REVIEW/ DECISION	
AFSCM 375-4 BLOCK NUMBERS	1-11	12-20	21	22-24	1-37	38-60	61-65	
RESPONSIBILITIES	HQ. USAF →			SPO CADRE	AFSC → SPO →			
MANAGEMENT OUTPUTS	ROC	TECHNICAL & EVALUATION REPORTS	RAD	PTDP or PSPP	RFP ← CONTRACTOR SOW CONTRACTOR PROPOSAL	CONTRACTOR REPORTS	UPDATED PTDP or PSPP	
PERSONNEL INPUTS		PS PLANNING STUDIES →	PS ANALYSES → FUNCTION/TASK ANALYSES TIME-LINE ANALYSES DESIGN STUDIES MAINTENANCE ANALYSES	ESTIMATES NO PERSONNEL TASKS REQ'D JOB POSITIONS SKILL LEVELS TRAINING REQ'D	MANNING STRUCTURE → SPECIFIED AS DESIGN REQUIREMENTS IN RFP & SOW	SYSTEM CONFIGURATION DESIGNED IN ACCORDANCE WITH PERSONNEL REQUIREMENTS REQ'S MANNING STRUCTURE (EG, PREL. QQPRI)		CONTINUING REFINEMENT of SYSTEM CONFIGURATION & MANNING STRUCTURE PED, FINAL QQPRI

ABBREVIATIONS

AFSC - AIR FORCE SYSTEM COMMAND
PED - PERSONNEL EQUIPMENT DATA
PS - PERSONNEL SUBSYSTEM
PSPP - PROPOSED SYSTEM PACKAGE PLAN
PTDP - PREL TECHNICAL DEVELOPMENT PLAN
QQPRI - QUANTITATIVE & QUALITATIVE PERSONNEL REQUIREMENTS INFORMATION
RAD - REQUIREMENTS ACTION DIRECTIVE
RFP - REQUEST FOR PROPOSAL
ROC - REQUIRED OPERATIONAL CAPABILITY
SOW - STATEMENT OF WORK
SPO - SYSTEM PROJECT OFFICE

4. Development of the PRD Inputs

Phase 1A/1B

The PRD inputs selected for inclusion in the study were those which would be developed as a product of the analyses performed during Phase 1A/1B in the System Definition stage (see Table II). This stage ordinarily follows the development of the PTDP in the Conceptual Transition phase and the writing of a Request for Proposal (RFP) during Phase 1A for contractor definition of the system. It precedes the Acquisition stage in which the system is designed in detail. Ordinarily contractor definition is the second phase (1B) of System Definition, but occasionally the System Planning Phase (1A) is contracted out, e.g., the 411L-AWACS presently under study. Hence, in referring to the developmental phase which the testing was designed to simulate, the term "phase 1A/1B" will be used.

During the contractor definition phase, the planning analyses reflected in the PTDP and RFP are refined in terms of an equipment configuration and an appropriate manning structure. The reason for confining the PRD inputs in this study to phase 1A/1B is that the major decisions influencing the system configuration are made in this phase. It is the effect of PRD on these major decisions which the study was designed to investigate. Although it may appear as if this ignores a great deal of human factors activity in the Acquisition stage, the detail design (including PRD) performed during Acquisition represents only an amplification and extension of decisions made earlier through progressive reiteration of earlier decisions. Only under conditions of a major redirection of system requirements will decisions made during earlier phases (1A and 1B) be reversed. Consequently, the influence PRD can have on system configuration during detail design is restricted to relatively molecular aspects of hardware configuration.

Criteria for Selection of PRD Inputs

The basis for selection of PRD inputs were the two following ground rules:

(1) Inputs must be logically derived from and be capable of being tied to the analyses required by the system development sequence. It is assumed that if PRD inputs are to be used by the design engineer, they must be related to the design problems which arise during system development. Theoretically, there should be a PRD input for every engineering milestone and every equipment input; in actuality, no such precise correlations of PRD and equipment inputs can be made. Since system development activities are iterative, certain inputs may be presented more than once with increasing detail and definition.

(2) Within the framework of system development requirements, as described in (1), PRD inputs must also be developed to satisfy certain personnel subsystem requirements (e.g., selection criteria, training courses) which demand certain inputs (e.g., skill and training requirements analyses).

The PRD inputs provided are listed in Table III and are also presented in Appendix I.

5. Determination of the Sequence of Providing Inputs

Because of the many iterations involved in system development, the developmental sequence included in this study can only approximate reality. In the development of this sequence, documentation describing system development were analyzed and the final sequence was checked with a number of experienced equipment designers.

Milestone Stages

The general milestone stages within phase 1A/1B were hypothesized to be as follows:

Once received, the design Statement of Work (SOW) is analyzed to determine system functions and sub-functions. Equipment and personnel functions based on these are listed and progressively refined. Responsibilities for performing system sub-functions are allocated between equipment and personnel. Both equipment and personnel functions are organized in terms of their sequential interrelationships in the form of functional flow diagrams. Based on system/mission requirements and the detailed function flow diagrams, a set of equipment that will implement these equipment functions are specified, and the equipment are described. Hardware for controlling the equipment is specified (e.g., controls and displays) and top level control panel drawings are developed. Maintenance analyses are then performed. These maintenance analyses are performed comparatively late in system development because it is impossible to determine maintenance requirements before sufficiently detailed equipment descriptions are available. Once control-display hardware has been specified, specific operating procedures can be developed. Based on equipment descriptions, a bill of material (complete list of hardware components) can be drawn up. The sequence is completed when contract end-item (CEI) specifications are drawn up. (The experimental design did not include the development of CEI specifications because these were considered to be only a summarization of the design information developed previously).

TABLE III

LIST AND DEFINITION OF MANPOWER REQUIREMENTS AND PRD INPUTS

I. Manpower Requirements

Item	Definition
(1) QQPRI data, including:	
(a) Number of personnel	Quantity of personnel required to perform subsystem operations, defined initially in terms of maximum number to be utilized, later in terms of actual number needed.
(b) Skill type	Characteristics of the job to be performed in terms of demands upon personnel.
(c) Skill level	Air Force skill levels required by the task, defined in terms of error probability, response time, and amount of assistance required.
(d) Proficiency	Skill characteristics which personnel should possess to perform the job satisfactorily.
(e) Task error-likelihood	Type of error which may occur during task performance.
(f) Personnel availability	Definitions of AFSC type possessing necessary qualifications to perform the job, together with the probability of such personnel being available for the job.
(2) Training requirements, including:	
(a) Anticipated training time	Time needed to train to given level of proficiency.
(b) Required aptitude	Job skills which training should provide.

TABLE III (concluded)

II. PRD Inputs

Item	Definition
(1) Lists of personnel tasks	Tasks defined in terms of personnel functions and equipment acted upon.
(2) Personnel/equipment flow diagrams	Diagrams illustrating the sequencing and interrelationships among tasks.
(3) Personnel/equipment analyses	Description of equipment characteristics required by tasks or effect of equipment characteristics on task performance.
(4) Task analysis, including:	
(a) Task structure	Task description in terms of function and equipment operated or maintained (See Item (1)).
(b) Task criticality	Consequences of task being performed incorrectly or not at all.
(c) Team performance	Number of personnel required to perform the task.
(d) Probability of successful task completion	Quantitative estimate of probability that the task will be completed successfully by personnel (the converse, error probability, also is provided).
(e) Task location	Approximate physical area (e.g., transporter, launch pad) in which the task must be performed.
(f) Task duration	Estimate of the time required to perform a task.
(g) Difficulty index	Estimated difficulty of task defined in terms of error probability and response time.
(5) Time-line analysis, including task frequency	Distribution over time, including overlaps, of individual task durations.

TABLE IV

BASIC DATA SOURCES FOR DEVELOPMENT OF PTPS INPUTS*

(1)	Titan III Student Study Guide, Propellant Transfer System ITL 624A-662	Revised 5/26/66
(2)	Task Analysis for PTPS Launch and Checkout Equipment (OSTF)	August 1959
(3)	Functional Flow Diagrams for PTPS	Revised 3/10/67
(4)	Maintenance Function Analyses for PTPS	Revised 7/17/67
(5)	Design Specifications for Major End-Items of PTPS	Revised 3/16/65
(6)	Operating Procedures for Major End-Items of PTPS	Revised 11/17/66
(7)	Schematics for Major End-Items of PTPS	Revised 11/17/66
(8)	Figure A Diagrams for Major End-Items of PTPS	August 8, 1963
(9)	Personnel Subsystem Data Books WS107A	
	Activity Flow Diagram	January 1961
	Launch Complex Operations	November 1962
(10)	Human Engineering Problem Report	February 21, 1964
(11)	Top Level Drawings of Major End-Items of PTPS	Revised 1/25/67
(12)	Panel Installation Drawings	Revised 4/5/67
(13)	Acceptance Criteria for Major End-Items of PTPS	Revised 5/8/64
(14)	Bill of Material for Major End-Items of PTPS (fuel)	Revised 1/20/67

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*The following classes of informational inputs were used to develop the PTPS inputs. The number of items within each class is so long that a complete bibliography is not included.

TABLE IV (concluded)

(15)	Component Lists for Major End-Items of PTPS (fuel)	Revised 1/5/67
(16)	System Installation Diagrams for PTPS	Revised 5/31/67
(17)	Equipment Specifications for Major End-Items of PTPS	Revised 7/11/67
(18)	Decal Drawings	Revised 8/31/66
(19)	Basic QQPRI for Titan II	January 1962
(20)	Forms C and C1 (Maintenance Analysis) for PTPS for Titan II	January 1962

Sequence of PRD Inputs

It is somewhat more difficult to specify the PRD inputs which should be provided at each milestone stage. Although AFSCM 375-5 (USAF, 1964) prescribes a sequence/milestone schedule for PRD inputs, this schedule is somewhat gross and replete with iterations. Tentatively the following sequence was hypothesized, based partially on 375-5 and partially on interviews with a number of experienced design engineers.

Personnel functions and function flow diagrams should be provided at the same time engineers are analyzing equipment functions. Personnel tasks and performance requirements should accompany the listing of required equipment and equipment descriptions. Personnel/equipment analyses should be provided as soon as initial equipment descriptions are available. Task analyses should be available at the time the engineer is deciding on control equipment. A description of personnel tasks involved in maintenance should be available when the designer is performing his maintenance analysis. Preliminary QQPRI should be available by the time operating procedures are being developed. Final QQPRI should be available prior to the development of the CEI specification.

Throughout the process, there are repetitive iterations of sub-stages designed to refine individual design outputs. The entire process is schematically represented in Figure 1. The test sequence as finally administered to subjects is shown in Table V and may also be reviewed in Appendix I.

One may ask whether the developmental sequence shown in Table V represents the "real world" sequence in which inputs are made and design activities are performed. The development of the design sequence in the study was admittedly one of the most difficult tasks the investigators had, because of the complexity of the activities involved. Subjects questioned concerning the realism of the inputs and the sequence of simulated events indicated that these were generally characteristic of the order in which they received their inputs. However, as shall be seen later, certain modifications in this concept of how system design proceeds during system definition were made necessary by the performance of the subjects.

Test Procedure

The general procedure for the individual sessions was to determine the effect of a particular input on the design task. At the start of any session, the engineer was told his design task, the inputs available to him were described, and he was asked to review them (in the event he had not reviewed them since he was first handed them at the close of the previous session). The subject then performed his design task.

Figure 1. PRD INPUTS IN SYSTEM PHASES 1A/1B

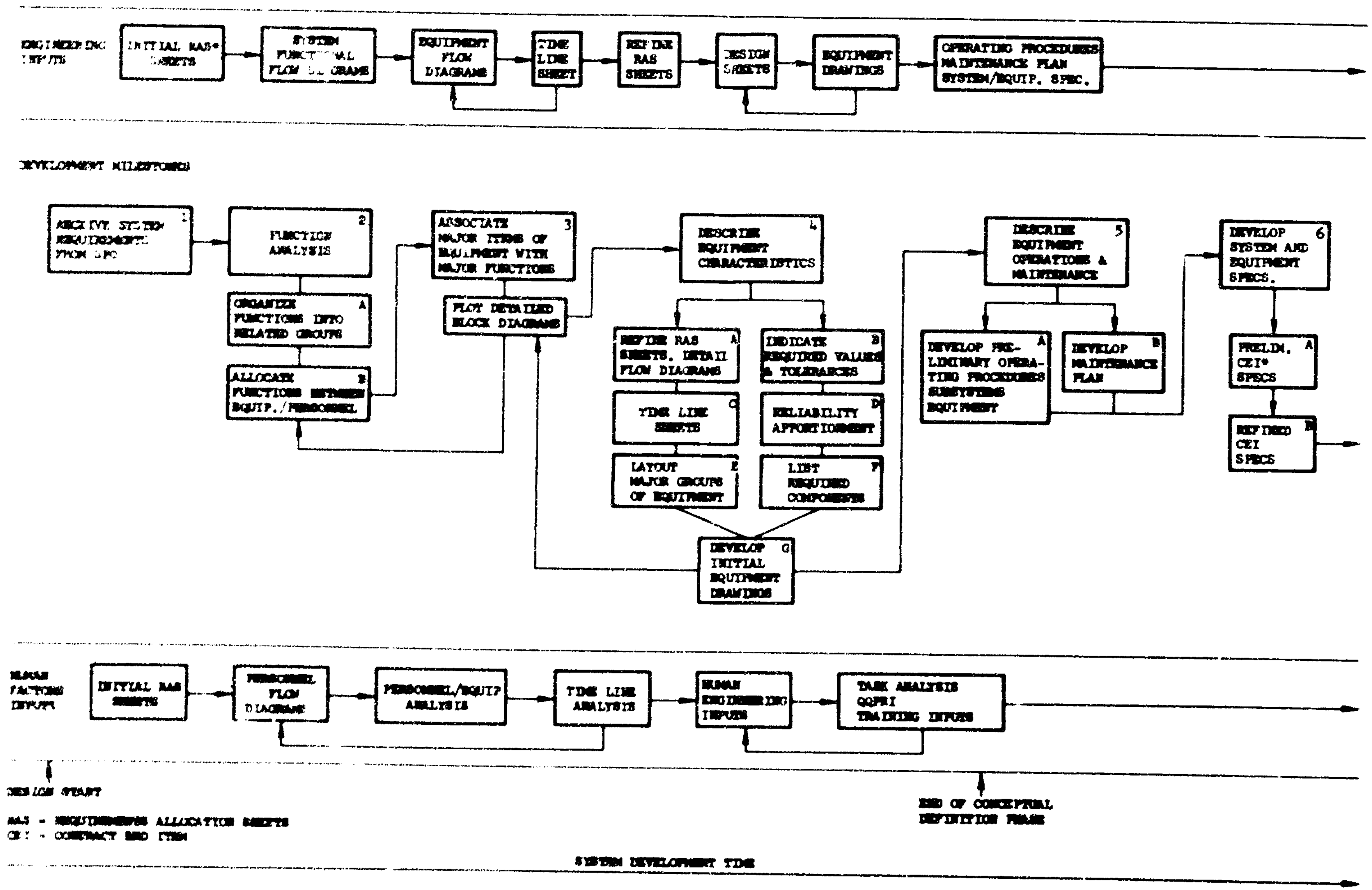


TABLE V

SEQUENCE OF INPUTS AND OUTPUTS FOR DESIGN OF EXPERIMENTAL SUBSYSTEM

1. Introduction

Group session. Subject is informed of the nature of the study.

2. Session 1

(a) Equipment input. Statement of work (SOW) which contains top level function flow diagrams.

(b) Personnel input. Flow diagrams of personnel operations, and SOW containing qualitative and quantitative personnel requirements.

(c) Required output. Subject will develop two flow diagrams of detailed subfunctions, one for transfer of fuel from transporter to RSV; the other, for fuel transfer between RSV and rocket tanks. Subject will indicate on the flow diagrams which functions are to be performed by personnel and which are to be performed by equipment.

The control group* will receive no personnel input; this procedure will be followed wherever a control group is noted in the following subsections.

3. Session 2.

(a) Equipment input. Partially filled out Requirements Allocation Sheets (RAS) (i.e., statement of design requirements).

(b) Personnel input. Personnel section of RAS filled out in addition to a more detailed personnel flow diagram which essentially replicates the RAS material in graphic form.

(c) Required output. Subject will describe the equipment required to implement design requirements. Control group.

4. Session 3.

(a) Equipment input. Supplementary sheets to RAS containing additional equipment detail.

*During each session, four of the designers were experimental subjects and two were control subjects (see page 45).

TABLE V (continued)

(b) Personnel input. Memorandum analyzing control-display requirements.

(c) Required output. Subject will review and amplify equipment descriptions; also, subject will develop equipment flow diagram. Control group.

5. Session 4

(a) Equipment input. Additional supplementary sheets to RAS.

(b) Personnel input. Preliminary task analysis of operations.

(c) Required output. Subject will develop list of control-display hardware required to operate the system. He also will indicate how many men of what types would be required to man the system. Control group.

6. Session 5

(a) Equipment input. New RAS sheets covering preventive maintenance. A maintainability design checklist will be furnished.

(b) Personnel input. Personnel section of RAS will include description of functional steps required to perform preventive maintenance. A maintainability design checklist will be furnished.

(c) Required output. Subject will provide flow diagram of detailed preventive maintenance subfunctions. He also will list any special maintenance/test equipment which would be required, indicating all special design features which would assist personnel performance of preventive maintenance. He also will indicate the number of maintenance men. Control group.

7. Session 6a

(a) Equipment input. None.

(b) Personnel input. Two time-line analyses (one for operation, one for preventive maintenance) per function to be performed.

(c) Required output. Subject will indicate how many control-display panels are required for his design and where they should be located. He will supply a rough sketch of the panels, indicating the functions to be covered and the approximate arrangement of the control-display devices. Control group.

TABLE V (continued)

8. Session 6b

(a) Equipment input. None

(b) Personnel input. Preliminary QQPRI, including numbers of personnel and position description.

(c) Required output. Subject will continue his panel layouts if he has not completed them. In addition, he will list the steps required to operate the control-display equipment. The control group specified for Session 6a also will be used for this session.

9. Session 7a

(a) Equipment input. None.

(b) Personnel input. Full scale QQPRI, including numbers of personnel, skill level, anticipated task reliability, training requirements, etc. The QQPRI also will include a list of potential human errors.

(c) Required output. Subject will list all potential operating problems and indicate design solutions for these. Control group.

10. Session 7b

This will be a continuation of Session 7a. Subject will review the design in the light of the QQPRI and will develop a complete list of equipment required. This list will be used by the cost estimators and reliability specialists in the final evaluation of subsystem design. Same control group as in Session 7a.

11. Session

(a) Personnel/equipment input. Memorandum from SPO reversing personnel requirements and directing redesign of the PTPS.

(b) Required output. Subject will review his past design and recommend design modifications to meet new personnel requirements. No control group.

TABLE V (concluded)

12. Session 9

Presentation of special problems. No control group.

13. Session 10

Presentation of special problems. No control group.

About a half hour before the end of the session (unless he obviously was not finished, in which case the session would be continued to the following week), the subject was informed that his work was to be reviewed. His output then was reviewed by the investigator with him to elicit any additional information and particularly the reasons why particular design features were incorporated. At the same time, the subject was questioned to determine whether: (1) he thought the input was useful, (2) the input was understandable and meaningful, (3) he used the input in deriving his design product, (4) the format of the input was satisfactory, (5) the timing of the input was appropriate, and (6) any additional information was needed.

At the close of the session he was handed the inputs for the next session and asked to study them if he had sufficient time.

The progressive development of the experimental subsystem was simulated by scheduling each subject individually for a minimum of 10 weekly three-to four-hour sessions (the length of the session depending on their speed. A few subjects spent hours between sessions elaborating their design outputs, a tribute to their interest in the project). In each session, the subject received increments of data corresponding to those which he would ordinarily have received as system design progressed and became more complex. For example, in the first session he would have available to him only the design statement of work, plus a list of personnel functions; by the fourth session he would have a vastly increased amount of equipment information plus a preliminary task analysis of operations; by the sixth session a time-line analysis, etc. Naturally, he would have available to him at each successive test session all the data (and his previous design outputs) from preceding sessions. At each session, the subject would be asked to supply certain design outputs which the investigators hypothesized should be affected by the PRD input for that session.

6. Determination of Design Outputs

The response secured from the subjects fell into two general classes, attitudinal or subjective outputs, and application, or product outputs.

When a PRD input was first presented to a subject he was asked (after he had reviewed the input) to indicate his personal response to the input. By this is meant that the investigators sought to determine how the subject felt about his immediate input; whether he understood it, and if not, why; whether he felt he could use the input, and if not, why; etc. Since the engineer must first be positively motivated to accept an input before he applies it, subjective responses were secured before proceeding to more objective outputs.

After the subject completed his subjective evaluation of the input, he was required to make use of the input by performing some engineering analysis or developing some engineering output, such as a drawing to which the PRD input was related. He was required to make use of the PRD input even though he may have indicated earlier that he could make little use of it. This was because his subjective response might or might not have been related to his objective output. (To anticipate the data, certain inputs overtly rejected by the engineer were still of value to his design in terms of, for example, reminding him of certain parameters he had overlooked.)

Subjective Outputs

The kinds of subjective outputs to be sought of the subject were as follows:

(1) Preference responses, e.g., I will accept/not accept the input.

(2) Utility responses, e.g., I can/cannot apply the input to system design.

(3) Knowledge responses, e.g., I understand/do not understand the input.

(4) Implication responses, e.g., I draw the following implications from the input; the following consequences result from the input.

(5) Schedule responses, e.g., the input is too early/too late/ just in time.

(6) Impact (effect) responses, e.g., my design is/ is not influenced by the input.

(7) Format responses, e.g., I would prefer the input to be in the following format.

Although there was some slight overlap among these responses (e.g., utility would seem to imply preference), each of these response types was considered separately because they could be combined in different ways, such as understanding an input but rejecting it as being inappropriately timed.

Product Outputs

The subject's product outputs could fall into two general classes:

(1) Analytic/decision responses, e.g., determination of functions, specification of system/equipment characteristics and operating modes.

(2) Drawing responses, e.g., physical layout of equipment. These might be affected in any number of ways. For example:

   (a) The number of components in a drawing could be increased or decreased;

   (b) The type of component, its function or the manner in which it operated could be changed;

   (c) Tasks might be added or deleted or their nature changed;

   (d) The number and type of personnel required might be modified, etc.

The specific design responses required of subjects are listed in Table V under the heading "Required Output."

The engineer's subjective responses (e.g., attitudes, preferences) may more directly indicate the utility of the PRD input than do his design outputs. The engineer had an opinion specifically about an input (e.g., yes, it is useful; no, it is not); his design output, such as a drawing, was influenced by a number of factors, only one of which might be the PRD input. Consequently, it might be more difficult to differentiate the effect of that input on the drawing from the other influential factors (e.g., cost, reliability and safety considerations).

Note that to extract the necessary data from subjects, the equivalent of an in-depth interview (debriefing) was conducted with subjects to explore the rationale for their responses.

7. Determination of Specific Measures

The measures of the effectiveness of MR and PRD inputs on subsystem design were derived from the specific objectives of the study (see page 14). To understand the rationale for these measures, it is necessary to consider them in terms of the overall experimental design of the study. This study design and its related effectiveness measures are discussed in detail in the following section.

C. EXPERIMENTAL DESIGN

Introduction

To explain the reason why the experimental design for this study was created the way it was and the reasons for the various analyses which were performed, this sub-section has been organized in terms of the specific questions which the study was designed to answer.

1. Do Differences in Manpower Requirements Influence Subsystem Design?

Quantitative Analyses

The six subjects were divided into two groups which received different personnel requirements in their design statement of work (SOW). Subjects in one group of three received as part of their SOW the requirement that they minimize the skill demanded of the operating personnel. This group was termed the Low Skill/High Number (of personnel) group, henceforth to be referred to as the LS/H# group, because in any design tradeoff the engineer-subjects could compensate for minimizing skill level by increasing the number of personnel they required.

Subjects in the second group of three (High Skill/Low Number (of personnel) or HS/L# group) received as part of their SOW (otherwise identical with that of the other group) the information that highly skilled personnel would become available as operators for their subsystem, and that consequently in any design tradeoffs they should minimize the number of personnel they required.

Presumably if the differing personnel requirements influenced the engineers' design, it would be reflected in the characteristics of the design outputs they produced (e.g., function flow diagrams, number and type of equipment components, operating problems anticipated, etc.).

Two general types of measures could be utilized in comparing the two experimental groups. Since each session required a specific design output, it would be possible to compare the performance of the two groups on a session-by-session basis. A list of the session-by-session analyses performed is presented in Table VI.

Alternately, one could expect that the overall subsystem design would be influenced by personnel requirements. That overall design would consist of the following design outputs produced during the testing and accumulated at the conclusion of the study:

TABLE VI

QUANTITATIVE MEASURES OF THE EFFECT OF PERSONNEL REQUIREMENTS AND PRD INPUTS

1. Session 1

Comparison of flow diagrams produced by the experimental and control subjects is as follows:

(1) The mean number of personnel-related functions produced by the experimental groups contrasted with the mean number of personnel-related functions for the control group.

2. Sessions 2-3

Comparison of experimental and control subjects in terms of the total number of personnel-related equipment items listed by subjects in completing their RAS.

3. Session 4

Comparison of experimental and control subjects in terms of:

(1) Total number of control-display hardware items noted.

(2) Comparison of manpower estimates.

4. Session 5

As in Session 1, comparison of experimental and control subjects in terms of:

(1) Number of maintenance/test equipment items listed.

(2) Manpower estimates.

5. Sessions 6a and 6b

Using the combined outputs of Sessions 6a and 6b (control panel layouts and operating procedures), a quantitative estimate of personnel performance (in probability terms) was made.

6. Session 7a

Comparison of experimental and control subjects in terms of number of operating problems described.

TABLE VI (concluded)

7. Session 7b

The equipment list supplied in this session was evaluated, together with the equipment descriptions, by specialists in pricing, reliability, safety and design specialists to secure rankings of the subsystem designs. The six designs were ranked in terms of the four sets of criteria individually and then a mean rank for each design was established. The rankings also were intercorrelated.

8. Session 8

Comparison made of the number and type of design changes recommended to satisfy changed personnel requirements.

9. Sessions 9 - 10

(1) Consistency of rankings given to design parameters, subsystem inputs, informational and manpower requirements.

(2) Mean rank order given to various developmental and informational inputs, e.g., equipment requirements, number of personnel available and task descriptions.

(1) control panel drawings, schematics, function flow diagrams;

(2) equipment descriptions, tolerances and bill of materials;

(3) operating procedures.

If one took these three products as a whole, it would be possible to compare the performance of the two groups in terms of the adequacy of their overall subsystem designs. This type of comparison utilizes what are generally termed as "system effectiveness" measures. They can be applied only to an evaluation of completed subsystem designs, not to output responses to the individual inputs. The reason for not applying them to individual output responses is because these measures are uniquely fitted for evaluation of total system complexes, rather than parts of systems.

Five types of subsystem design analyses were possible:

(1) Cost. Cost is taken to mean the cost required to fabricate and/or procure the first production model of the system, including required maintenance equipment. Because of study limitations of time, and money, it does not include research and development, testing, operating or support costs which would be included in a thorough analysis of life cycle costs.

(2) Design adequacy. Design adequacy is defined as the subsystem's potential for efficient performance based on its physical configuration. Although this evaluation must by its nature be subjective, it is measured by criteria such as satisfaction of all required subsystem functions, simplicity of operation and redundancy of elements where required.

(3) Safety. Safety involves two factors: personnel hazard and protection of the equipment from catastrophic failure. The specific assumptions utilized in the safety evaluation are listed in Appendix II.

(4) Reliability of performance: equipment. Reliability is the probability of a device performing its purpose adequately for a period of time intended under the operating conditions encountered. Simply stated, it represents the probability of successful operation. In the context of the present study, a reliability measure of the subsystem design

indicates quantitatively how well designed the subsystem is for performance. (Obviously, the design adequacy and equipment reliability measures are related, the former representing a more subjective evaluation of performance probability but probably containing some elements not contained in the latter.) It is hypothesized that a more effectively designed subsystem--one of the hallmarks of which would be the consideration of personnel factors in the design--should have a higher reliability. A detailed description of the procedures by which subsystem design reliability is estimated would be of interest largely to the equipment reliability engineer; hence it is included in Appendix II.

(5) Reliability of performance: personnel. To the extent that personnel requirements and PRD inputs are incorporated in subsystem design, one would expect that the anticipated reliability of subsystem personnel performance would be considerably increased. The personnel component of overall subsystem reliability (commonly termed "human reliability") should be most directly, immediately related to personnel inputs, whereas equipment reliability would be only indirectly affected by such inputs.

Hence it was decided to make a human reliability estimate of the completed subsystem designs and to compare this estimate with the equipment reliability estimate of the same design.

Because the technique for developing human reliability estimates is quite new, there is some point to describing it in detail.

Human reliability indices predict the effectiveness with which personnel will utilize the system in the operational environment. The technique, which is an application of reliability engineering procedures to human performance problems, is discussed in brief in Hornyak (1967).

Briefly, the technique involves four major steps:

(1) Analysis of the system or subsystem into discrete measureable units. The technique takes advantage of the usual task analysis or--in the case of the present study, the operating procedures and control panel diagrams developed by each subject--to derive these units, each of which contains information concerning the operator's behavior in terms of initiating stimuli, mediating processes, and motor responses. Consequently, the major work involved in applying the technique is already performed as part of the usual subsystem analysis.

(2) Analysis of the subsystem operations in terms of certain parameters of correct performance of the unit. The list of 13 parameters includes such aspects as the presence or absence of feedback, the degree of stress imposed on the operator, type and number of stimuli presented, etc.

(3) Assignment of predictive values (probability of successful task/unit performance) to the behavioral units. This is done on the basis of tables of expected probabilities derived from data found in the experimental literature. (Tables of predictive values are included in Hornyak (1967)). For each parameter found influencing the behavioral unit, an expected decrement of performance is ascertained from the tables, and that decrement is subtracted from 1.0 (so-called "optimal" performance) to secure a probability of successful task performance.

(4) Combination of unit probabilities into a total, unitary figure of merit reflecting the overall expected probability of successful utilization of the subsystem. The individual unit probabilities are combined mathematically on the basis of the independence/dependence relationships among the units.

The whole approach parallels the development of reliability indices describing the expected probability of equipment functioning. Although the technique is still embryonic and depends a great deal on the availability of performance data from the experimental literature, it appears perfectly suited for application to the problem of comparing design configurations.

Qualitative Analyses

During the simulated development cycle (at session 8), the personnel requirements given the two groups of subjects were modified by exchanging these requirements between the two groups. In other words, the LS/H# group had the number of personnel available to them cut in half (the precise number depending on the subject's own manpower estimate developed in session 4), but the skill level of the remaining crew members was correspondingly raised. The HS/L# group had the number of personnel available to them raised (depending on their original manpower estimates) but the skill level has correspondingly reduced.

The subjects were then required to analyze their previous design configurations in terms of the new personnel requirements. Presumably, if the reversed requirements had any effect, they should result in revised designs.

Information concerning the influence of personnel requirements was also secured by interviewing the engineer-subject, particularly at the conclusion of the first session and during sessions 9 and 10. Since the initial personnel requirements were contained in the SOW which was the primary input for session 1, subjects could be asked the following questions: How do you think the personnel requirements in the SOW will affect your design? Do you think they will have any significant effect on your design? In what way? Similar questions were asked at the conclusion of session 8.

Several of the questions in sessions 9 and 10 (see Appendix I) dealt with the influence of varying numbers and types of personnel on equipment design. For example, in one question, subjects were asked how they would design a propellant transfer system if only two personnel were available; or to contrast the effect on their design of Marquardt technicians vs. Air Force personnel.

2. Do Personnel Resources Data Inputs Have a Significant Effect on Equipment Design?

Quantitative Analyses

The most effective way of demonstrating that a personnel resources data input has an effect on design is to contrast the performance of subjects who have been exposed to that input (i.e., experimental subjects) with the performance of other subjects who have not received that input (i.e., control subjects). Although it is somewhat unrealistic to assume the absence of any PRD inputs at all in the development of a system created to military specifications, it seemed worthwhile to maximize the opportunity of demonstrating that under optimal conditions the PRD input will have a significant effect on design.

Consequently, in addition to the two experimental groups, it appeared worthwhile to add a control group which did not receive the PRD input. It was undesirable, however, to segregate two or three of the six subjects as a permanent control group. This would create the artificial situation referred to previously of a group of design engineers who never experienced PRD inputs through the simulated developmental sequence. Moreover, it would drastically reduce the number of subjects exposed to each experimental variable.

Consequently, it was decided to create a control group by systematically selecting two different subjects in each test session who would not receive the PRD input for that session.

Thus, in session 1, subject 3 in both groups acted as a control by not receiving the PRD input; all others received their appropriate inputs. Note that all subjects, both experimental and control, always received

their equipment inputs in every session; the control subjects differed from the experimental subjects only in not receiving the PRD input.

In session 2, subject 2 in both groups acted as a control, while all other subjects (including those who in the previous session had acted as controls) received both equipment and PRD inputs. The control subjects who in session 2 became experimental subjects now received the PRD input they missed in the previous test session (1); however, it did them no good for that previous session's work. They were given the PRD input, however, so that they could catch up with the other subjects in their group.

This process was continued throughout the test sessions as shown in Table VII, with the exception of sessions 8, 9 and 10, which were presented to all subjects in the same manner.

The major advantage with this procedure of selecting control subjects was that, first, it avoided the artificiality of eliminating all PRD inputs for the control group; second, it permitted us to examine what the subject's reaction to the PRD input was when it arrived late. Obviously, when a subject who was a control in session 2 received the PRD input for session 2 in session 3, that input was, as far as he was concerned, late for the design work he performed in the previous session. Finally, while only two subjects formed the control group, their variability was representative of the entire subject population, which made them much more representative of the engineering population as a whole.

The one disadvantage of this scheme, however, is that it permits us to compare the performance of experimental and control subjects only within each session.

Qualitative Analyses

The effect of individual PRD inputs on equipment design was also determined subjectively, by asking the engineer the following typical questions during the debriefing which concluded each session:

(1) Does the new input(s) provide you with enough information to perform the particular design output required?

(2) Did you find the (session PRD input) useful in performing today's task?

(3) Could you apply this information (i. e., PRD input) to your (design) analysis?

(4) What equipment design implications can you draw from the (PRD input)?

TABLE VII

EXPERIMENTAL DESIGN FOR STUDY

Group	Ss	Sessions									
		1	2	3	4	5	6	7	8	9	10
LS/H#	1	0	0	X	0	0	X	0	0	0	0
	2	0	X	0	0	X	0	0	0	0	0
	3	X	0	0	X	0	0	X	0	0	0
HS/L#	1	0	0	X	0	0	X	0	0	0	0
	2	0	X	0	0	X	0	0	0	0	0
	3	X	0	0	X	0	0	X	0	0	0

Reversal of personnel requirements

Special problems

Ss - Subjects
0 - Experimental Subject
X - Control Subject
LS/H# - Low Skill/High Quantity
HS/L# - High Skill/Low Quantity

During sessions 9 - 10, subjects were asked to rank the priority of various parameters (e.g., equipment characteristics, cost, reliability, accessibility) to be considered during the design of various subsystems, and to rank the relative importance of all the inputs provided to them during the study.

Summary of Experimental Measures of Manpower Requirements and Personnel Resources Data Impact

The categories of experimental measures possible to answer the questions regarding impact of MR and PRD can be summarized as follows:

(1) To determine the effect of PRD data on design: session-by-session comparisons between all experimental subjects combined and the control subjects.

(2) To determine the effect of manpower requirements on design:

(a) Session-by-session comparison between HS/L# and LS/H# groups.

(b) Total subsystem design comparisons (i.e., reliability, cost, safety, design adequacy) of designs produced by HS/L# and LS/H# groups.

(c) The effect of changing manpower requirements after subsystem design has been completed (session 8).

Note that it is impossible to make total subsystem comparisons between experimental and control groups, because in the present experimental design there is no clearly distinguishable control group as a group, all subjects having at one time or another participated in the study as control subjects.

One other general statement concerning the experimental design should be made. Tests of significance between experimental treatments (e.g., between HS/L# and LS/H# groups, and between these groups combined and control subjects) were not possible because the number of subjects in any comparison was never more than four. Moreover, session-by-session data could not be combined to increase the number of data points because each session involved a somewhat different design output. Comparisons between the various groups in terms of their design outputs have therefore been confined only to reporting of means. It is, therefore, necessary to look for measures of significance in terms of the consistency of results. If one group or the other is consistently higher or lower than the other, then the likelihood that a genuine phenomenon exists.

The rankings made by subjects in sessions 9 and 10 were tested for consistency by the Kendall W statistic (Siegel, 1956). The Spearman rank order correlation was employed on one ranking item (see Table 13) to determine the relationship between rankings of the present subjects with those of the previous studies. Rankings of the overall subsystem design outputs were correlated using the W statistic.

3. At What Stage of Subsystem Development do MR and PRD Inputs Have Their Greatest Input on Equipment Design?

Because this study did not vary the sequence in which PRD inputs were presented to subjects, it is impossible to present any quantitative data on this point. However, it was possible to infer the usefulness and impact of the individual PRD inputs as a function of stage of development by asking questions such as the following at the conclusion of each session:

(a) What information would you ordinarily receive at this stage of system development? Would this information be sufficient?

(b) Is the PRD input (presented at this session) too early, too late or just right in time?

(c) What additional information would you want to have?

(d) If you knew the number and type of personnel you were going to have, would this help you in performing the design task?

4. In What Form are PRD Inputs Most Effectively Used by Designers?

Again, the information relative to this question is largely qualitative. The following questions asked of the engineer during the individual session debriefings are pertinent:

(a) Do you have any difficulty understanding the personnel input? Why?

(b) Where two versions of the same PRD input were presented, which version did you find more useful?

In addition, one of the questions presented during sessions 9 - 10 dealt with the form in which personnel requirements were supplied in the design SOW. These requirements varied in format from the qualitative and general to the quantitative and highly specific. Subjects were asked to anticipate the impact of the various requirements if they were required to design to these.

5. What is the Design Engineer's Concept of Human Factors in System Design and His Attitude Toward PRD Input?

Quantitative Analysis

By asking the design engineer to supply manpower estimates at session 4 and at the conclusion of the study, it is possible to determine:

(a) If he had a concept of the manning required by his subsystem (that is, whether or not he could estimate the number and type personnel needed);

(b) The consistency of his manning concepts as additional inputs were provided;

(c) The relationship of his manning concept to the particular type of design concept he developed?

For example, it is possible to analyze the consistency of the designer's manning concept by determining if it changed over the course of the study. The validity of that manning concept is determined by correlating his design concept (categorized in automation terms as, completely automated, partially automated and remote-manual) with the number of personnel he felt he needed to man his subsystem. If the correlation was high, one could say the engineer's manning concept was realistic; if it was low, it was unrealistic.

Qualitative Analysis

Engineer attitudes toward PRD inputs and human factors as a whole were determined by analysis of subject reactions to individual PRD inputs and to questions asked in the debriefing sessions at the conclusion of individual sessions. In this respect, it should be reiterated that the investigator was not limited to a fixed schedule of questions, and that the specific questions asked invariably led to an in-depth interview.

6. How Does the Manner in Which the Engineer Designs Affect the Utilization of PRD Inputs?

The engineer's design style was determined by analysis of the following indices:

(a) The speed with which he developed his initial equipment configuration;

(b) The amount and quality of the analysis he performed prior to and during the development of the equipment configuration;

(c) The number and extent of changes to that configuration as testing progressed;

(d) The design criteria he reported using as the basis of his design;

(e) Expressed attitudes of acceptance or rejection of PRD inputs;

(f) The practices he reported as being characteristic of the manner in which he ordinarily designs.

These were analyzed in relation to the following PRD utilization factors:

(1) Usefulness of the PRD inputs provided;

(2) Timeliness of the PRD information supplied;

(3) Intelligibility of the PRD information;

(4) Applicability of the PRD inputs to the design outputs;

(5) Implications for design drawn by the engineer from the PRD input.

7. <u>How Available is Information as a Whole to the Engineer During Design?</u>

Data on this point was secured from questions such as the following:

(a) Do you have enough (equipment and personnel) information about (the design task presented) to accomplish your task?

(b) What additional information would you want to have about (the design task presented)?

(c) What information would you ordinarily receive at this stage of system development? Would this information be sufficient?

(d) When would you ordinarily expect to receive information of this sort (e.g., the PRD input)?

(e) Could you (would you) have derived this information (presented at the individual session) on your own?

SECTION III

RESULTS AND CONCLUSIONS

A. RESULTS

Introduction

Before proceeding to the specific study results, it may be helpful to the reader if he refers to Appendix III, which presents some representative design outputs which subjects produced and which will give him a better "feel" for the nature of the design process. The following is a list of the outputs illustrated in Appendix III:

(1) Figures 12 and 13 are two schematic diagrams developed by subject K during the first session, with minor changes made as simulated development progressed.

(2) Table XV is a partial copy of the equipment description which accompanies that flow diagram.

(3) Figure 14 is an initial control panel sketch by subject D.

(4) Table XVI is a copy of a detailed operating procedure which accompanies the schematic diagram in (1) and the control panel sketch in (3).

(5) Table XVII is a copy of a representative list of hardware components created by subject J.

These samples indicate the rather substantial amount of detail to which the subjects went in their design.

Because of the complexity of the study results, we will summarize the study results before we proceed to specific details. The organization of this section is outlined as follows:

A. Summary of study results:

B. Detailed results categorized by the individual questions which the study sought to answer. Under each question, then, in the following order the reader will find

1. Quantitative data pertaining to the individual question;

2. Qualitative data relevant to that question;

3. Conclusions reached with regard to the question.

Summary of Results

(1) Do differences in manpower requirements influence subsystem design?

(a) Session-by-session data provide somewhat ambiguous results. With the exception of session 4, where the HS/L# engineers listed significantly more control-display hardware needed to operate their subsystems, the other differences between the LS/H# and HS/L# groups were small and not particularly significant.

(b) Session 8 results (in which personnel requirements were exchanged between the LS/H# and HS/L# groups) indicated that half the subjects would make some change in their subsystem design, if not in the physical hardware itself, then in the subsystem operating procedures. There was, however, considerable resistance to the idea of changing design at that late date, even though for LS/H# subjects the reduction in the availability of personnel made their subsystems inoperable.

(c) The LS/H# group had a substantial superiority in equipment reliability over the HS/L# group, which may be attributed in part to the need to compensate in their design for the requirement to design the subsystem for lower skilled personnel.

(d) When subjects rated (see Table VIII) the anticipated effect on design of various personnel requirements in the SOW, those requirements which were concrete, precise and quantitative were rated as highly influential on design; those formulated in general less specifically design relevant terms were rated as having slight or no effect upon design.

(e) Apparently, when personnel requirements are sufficiently specific to the new design and when they constrain design, they do have an important effect upon that design. In the present study, the effect of personnel requirements was not as high as it should have been for several reasons: (1) the personnel requirements specified in the experimental SOW set high upper limits so that they did not constrain these subjects; (2) although subjects indicated that skill

level and personnel quantity are independent parameters (i.e., higher skill level does not compensate for fewer personnel and vice versa), the combination of skill level and personnel quantity in the groups tended to cancel out their differential effect; and (3) the response to personnel requirements tends to be quite idiosyncratic.

(f) Acting on the hypothesis that differences in personnel requirements should be reflected also in engineer's manning concepts, we asked subjects to estimate the manning needed for their subsystems during the fourth session and at the end of the study.

(g) The engineer also independently develops a manning concept, in some cases simultaneously with the creation of the design configuration, in other cases (developed later), as a deduction from that design configuration. This concept includes both personnel number and skill level parameters, but does not include training.

(h) The LS/H# group estimated a mean of 8.3 personnel, and the HS/L# group estimated a mean of 6.0 personnel, well below the upper limits set by the SOW of 12. The results are consistent with the hypothesis described in (a) herein. In all cases, during debriefing interviews, subjects resisted the idea of using lesser skilled personnel.

(i) Manning estimates were almost completely unvarying throughout the simulated design process. The QQPRI input, which deviated from subjects' estimated manning, did not cause them to change that manning. As described previously, engineers are highly resistant to suggested changes, once the basic subsystem configuration (which would include the estimated manning) is established.

(j) There was little correlation between the engineers' manning concept and the type of subsystem he developed. For example, the completely automated design required three times as many men as the semiautomated design and more than the remote-manual subsystems. This suggests that engineers' manpower concepts are not realistic.

(2) <u>Do Personnel Resources Data Inputs Have a Significant Effect on Equipment Design?</u>

(a) The primary analysis here is between experimental (those receiving PRD inputs) and control (those not receiving PRD inputs) subjects on a session-by-session basis. Comparisons between these groups are available for five sessions. In three of the five sessions, the experimental subjects produced a larger number of personnel-related design outputs (e.g., larger number of control-display hardware items listed) than the control subjects. In one session (the first) the difference between experimental and control subjects was essentially zero, while in another session the difference was in favor of the control subjects. It appears then that the PRD inputs do have an effect on design outputs, but the effect is less than one would desire.

(b) Expressions of opinion from the subjects in debriefing interviews indicated that half the subjects felt that PRD inputs were of some value, while the other half did not. Even where the PRD input was rejected by the engineer, it served a useful purpose as a reminder of factors the engineer may have overlooked (session 5).

(c) Several reasons for this less than maximal PRD effectiveness were noted: (1) the engineer responds to an input primarily in terms of its importance as a design constraint; most PRD inputs are purely information or predictive. Half the subjects indicated that PRD inputs would have had a significant effect on their design if they had been included as requirements in the SOW, (2) engineers had difficulty interpreting the significance of PRD inputs (e.g., skill level description) in design-relevant terms, and (3) because the design concept is developed so rapidly, many PRD inputs supplied in later design stages have been anticipated by engineers.

(3) At What Stage of Subsystem Development do MR and PRD Inputs Have Their Greatest Effect on Equipment Design?

Because the engineer develops the hardware details of his design concept so rapidly (the basic concept was complete for all subjects in session 1) and because he is responsive primarily to design requirements and constraints (which are usually included in the design statement of work, to which all subjects referred most often), MR and PRD inputs have their greatest impact on equipment design when they are incorporated as part of the statement of work which initiates that design.

(4) <u>In What Forms are PRD Inputs Most Effectively Used by Designers?</u>

(a) The relevant evidence is derived from debriefings at the conclusion of individual test sessions and from rankings of PRD inputs made in sessions 9-10. Although the most important inputs to the engineer are his SOW and other equipment information, because these supply him with data on design requirements and constraints, the most important PRD inputs to the engineer are the performance requirements data on the Requirements Allocation Sheets, personnel-equipment analyses (e.g., control-display memoranda), lists of tasks and task descriptions. Note that these are all relatively concrete and interpretible in terms of subsystem operations. A PRD input is preferred to the extent that it describes or can be easily related to concrete operations. Least useful to engineers is information dealing with training requirements, personnel availability, time-line analyses, probability of task completion and personnel descriptions, because these are relatively abstract in character.

(b) Some of the same reasons which determine the overall effectiveness of PRD inputs are responsible for determining which of these inputs are most useful. The engineer's overwhelming concentration on physical parameters and his unawareness of human factors ensure that the only PRD inputs he can use are those which can be most clearly tied to physical parameters, e.g., lists of tasks and task descriptions which he interprets as operating procedures; personnel-equipment analyses which deal with relatively molecular aspects of the equipment configuration, etc. As was referred to earlier, the engineer lacks the ability to interpret data phrased in behavioral terms, like skill level, proficiency, difficulty, etc., so that in order for PRD inputs incorporating such concepts to be accepted, they must be rephrased in terms closer to the engineer's experience.

(5) <u>What is the Design Engineer's Concept of Human Factors in System Design and His Attitudes Toward PRD Inputs?</u>

(a) There was a general tendency on the part of engineers to ignore operator considerations in the very brief analysis which preceded his development of the subsystem configuration. Because of the emphasis upon safety, personnel factors related to design for safety were a major expressed consideration in his design.

(b) The engineer has a concept of the personnel subsystem as being largely human engineering of the molecular "knobs and dials" type. Hence, he considers that most PRD inputs should be provided relatively late in subsystem design.

(c) The engineer generally considers the personnel aspects of the subsystem as deriving from and dependent upon equipment characteristics. He resists the concept of personnel resources analysis being a partner in the subsystem configuration or as controlling it in any manner.

(6) <u>How Does the Manner in Which the Engineer Designs Affect the Utilization of PRD Inputs?</u>

(a) Most important in terms of its effect upon the engineer's use of PRD is the excessive speed with which he proceeds to develop his design concept. In every case, this concept was fully developed by the end of the first test session. The consequences of the speed with which he develops the hardware details of his design are that the system analytic process, during which human factors involved in the design would be considered, is highly compressed, so that in fact there is little or no consideration of human resources problems.

(b) That the initial system concept is modified in only very minor details as design progresses is also quite important. Consequently, most of the PRD supplied after the start of design are essentially irrelevant to the engineer. PRD can either coincide with the engineer's system concept, in which case they serve merely to reinforce that concept, or they will conflict with that concept, in which case they will be ignored or rejected.

(c) The major reasons for the speed with which the engineer designs is his reliance on his past experience and his use of the design stereotypes which he brings to the design problem.

(d) The engineer relies primarily on inputs which are interpreted by him either as design requirements or design constraints. Thus, the major information source for the engineer is the SOW and associated equipment information. Hence, PRD which cannot be interpreted in this manner are ignored.

(e) Because the engineer designs primarily in terms of requirements and constraints, many engineers resist the introduction of information which may constrain his design. The following antithetical attitudes are expressed according to the engineer's characteristic design style: either he prefers to receive as much information as possible as a guide to his design or he resists what he considers excessive information as limiting his creative freedom.

(f) The subsystem designs produced by the engineer-subjects show considerable variations in basic design concept. These differences are due to a number of factors: (1) variation in the manner in which the originating design SOW is interpreted, in terms of the priorities placed on design criteria described in the SOW, such as cost, safety, reliability, and (2) the experimental stereotypes he possesses, such as rejection of automated systems (in general) or rejection of manual systems (in general). The major differences in design are reflected in differences in equipment and personnel reliability, safety and cost.

(g) Three kinds of subsystem designs were developed: (1) Four of the six could be described as remote manual; one as semiautomated and one as completely automated. Three of the four remote manual systems were developed by the HS/L# group; the two automated systems by the LS/H# group. However, these differences cannot be ascribed to varying personnel requirements, but rather to the way the individual engineers interpreted the SOW.

(h) The design criteria which the engineer typically applies in his design are indicated by ranking supplied by subjects in Item 9-1 (see Table XII). In order of decreasing importance, these are: physical equipment characteristics, reliability, cost, complexity of operating procedures and the effect of equipment characteristics on personnel.

(i) The foregoing design process characteristics are startingly similar to characteristics observed with the 30 engineers tested in the two previous studies by Meister and Farr (1966) and Meister and Sullivan (1967).

(7) How Available is Information as a Whole to the Engineer During Design?

(a) Design engineers usually have less information than was provided them in the study. This was particularly true of PRD information. Engineers generally prefer as much equipment-related information as possible, and as early as possible, but this is true of PRD inputs only in the case of certain subjects.

(b) In the subjects' opinions, the information provided them in the study was more than sufficient for them to accomplish their design tasks. The only exception to this was a lack of detail describing the characteristics of the space launch vehicle.

(c) Engineers felt that they could have developed certain types of PRD information on their own, e.g., personnel/equipment analyses and task data, i.e., information closely related to the equipment functioning of the subsystem. However, they would not and could not have developed QQPRI on their own.

Detailed Results

1. Do Differences in Manpower Requirements Influence Subsystem Configurations?

The six subjects were divided into two groups which received different manpower requirements in their design SOW. The LS/H# group received the instruction that they minimize the skill required of operating personnel, even if it necessitated a larger number of personnel. Subjects in the HS/L# group were required to minimize the number of operating personnel even if it necessitated an increased skill level.

Quantitative Results: Session-by-Session Measures

Measures of the effect of manpower requirements on the design outputs of the two groups are available from session-by-session analyses. These results are based on all six subjects, since presumably the differing manpower requirements were effective even when control subjects received no PRD inputs.

It was hypothesized that the HS/L# group would include in their subsystem design a greater number of manual functions than would the LS/H# group, because the former engineers would have more confidence in the ability of higher skilled personnel to perform subsystem control tasks.

This hypothesis assumed that a larger quantity of personnel would not be considered by the engineers of the LS/H# group as compensating for the lesser skill of the personnel available to these designers. Consequently, the LS/H# engineers would be more inclined to automate their subsystems.

(1) Session 1. Differences in number of personnel-related functions, e.g., manual interfaces, and primarily manually operated valves specified in the schematics produced by the two groups:

HS/L#			LS/H#		
S		No. of Functions	S		No. of Functions
1		7	1		10
2		4	2		3
3		3	3		8
	Total	14		Total	21
	M	4.7		M	7.0

The small number of subjects, as also the small number of functions (perfectly understandable at this gross level of system description), makes it impossible to draw any meaningful statistical conclusions from the data. The differences do not appear to be significant, however. These differences are largely due to the degree to which the individual engineer initially detailed his design.

(2) Sessions 2-3. In sessions 2-3, subjects were required to describe the equipment which they would need to implement their design concept. Again, the number of personnel-related equipment items (e.g., manually operated valves) which they required is of interest.

The mean number of items noted by the HS/L# group is 58.7; the mean number for the LS/H# group is 68.0. The individual values are listed below:

HS/L#			LS/H#		
S		No. of Items	S		No. of Items
1		35	1		43
2		59	2		70
3		82	3		91
	M	58.7		M	68.0

Again, because of the small number of subjects in each group, any statistical comparisons would be meaningless. However, these differences do not appear to be significant, again for the same reason cited previously for session 1.

(3) Session 4. In this session, subjects were asked to list the control display hardware needed to run their systems. It is, therefore, possible to compare the two groups in terms of the number of control-display hardware items they required. The results are shown below:

HS/L#		LS/H#	
S	No. of Items	S	No. of Items
1	250	1	50
2	50	2	142
3	185	3	118
M	161.7	M	103.3

The difference here in contrast to the previous three sessions, is quite substantial, but again the small number of subjects prevents meaningful statistical comparison of the two groups. The two subjects who responded with only 50 items were control subjects (i.e., those who had not received the PRD input for that session). When control subjects are eliminated, the difference is even greater, HS/L# subjects having a mean of 217 items, and LS/H# subjects having a mean of 130 items.

It is necessary to explain why the differences between the two groups in session 4 are so great in contrast to the small differences noted in previous sessions; and why the HS/L# group produced more control display hardware, when in previous sessions they had had fewer subsystem functions and manually operated valves.

As indicated previously, it is hypothesized that the HS/L# group felt it could assign more manual tasks to its small number of personnel because these personnel were highly skilled. Consequently, they permitted their technicians to perform their tasks manually (i.e., by switching controls in response to subsystem display indications) whereas the LS/H# group felt that they had to automate subsystem processes more because lower skilled personnel could not be relied on. Since the HS/L# group designed their subsystem so that its control processes were to be

performed manually, they had to include a substantially greater number of controls and displays to accommodate these manual tasks.

The apparent reversal between the results of session 4 and sessions 1-3 (the HS/L# group producing a high number of personnel related equipment in session 4, whereas they produced a low number in sessions 1-3) is accounted for by the fact that the listing of control-display hardware is a much more direct, sensitive measure of response to manpower requirements than is the listing of subsystem functions and manually operated valves which are tied only indirectly to manpower requirements. The manual valves were required by all engineers because only in this way can propellants from the storage tanks to the launch vehicle could be performed in different ways depending on the degree of automation in the design concept.

(4) Session 5. In session 5, subjects were presented with maintenance functions and tasks and asked to indicate the maintenance/test equipment they would require to implement their systems. It was hypothesized that the group more responsive to personnel requirements would list more test equipment. When the two groups are compared in terms of the number of maintenance/test equipment items listed in the equipment descriptions, the following appears:

HS/L#		LS/H#	
S	No. of Items	S	No. of Items
1	0	1	2
2	3	2	5
3	1	3	1
M	1.3	M	2.7

The essential information which one can derive from session 5 is that subjects were not particularly maintenance conscious, as evidenced by the low number of items they produced (one subject requiring none). The difference between the two groups cannot, therefore, be considered significant, even though the LS/H# group produced twice as many items of test equipment as the HS/L# group. The larger number of test equipment items for the LS/H# group was due largely to one man (subject H) who designed the only completely automated subsystem and who might, therefore, be expected to be more concerned about maintenance.

(5) Sessions 6A and 6B. The outputs of these sessions were designed to be used for analysis of the total subsystem design; hence they will be discussed later.

(6) Session 7A. In session 7A, subjects were asked to list the operating problems they could anticipate in the functioning of their subsystems. A comparison can be made between the two groups in terms of the number of personnel-related problems noted by subjects. This is shown below:

HS/L#		LS/H#	
S	No. of Problems	S	No. of Problems
1	7	1	6
2	18	2	9
3	12	3	9
M	12.3	M	8.0

The increased number of operating problems noted by the HS/L# group can be explained in terms of the larger number of manual functions (see results of session 4) which this group included in their subsystem design. Since personnel were used by this group to control the subsystem directly (by switch operations, on the basis of displayed information), it could be assumed that more operating problems would arise in this situation than in the LS/H# designs where control operations were, despite the larger number of personnel, more automated.

(7) Session 8. Session 8 results will be evaluated in the qualitative subsection of this analysis, since the outputs produced during this session do not lend themselves to quantitative evaluation.

(8) Sessions 9-10. Only one of the items presented in these two sessions is relevant to the question of the influence of personnel requirements in the SOW.

Fourteen statements representing requirements of varying degree of concreteness, specificity and quantity were presented. Subjects were required to indicate whether the individual statement would (1) greatly affect design, (2) slightly affect design, and (3) have no effect on design. Unfortunately, subject consistency failed to be significant when tested with Kendall's W at the .05 level. Thirteen of these statements described various types of PRD, e.g., personnel availability, maximum number of personnel permitted, training, etc.

TABLE VIII

RATINGS BY SIX DESIGNERS OF THE INFLUENCE OF VARIOUS TYPES OF PERSONNEL REQUIREMENTS UPON DESIGN

	Number of Responses in each Category*			Requirement
Item No.	I	II	III	
1	6			In order to avoid safety problems, all subsystem operations will be performed from a remote control station.
2	6			For reasons of economy, all subsystem operations will be performed manually, consistent with safety provisions.
3	6			Subsystem design and production of the initial system cannot exceed $200,000.
4	6			The following subsystem operations will be performed manually: transfer of propellant from the railroad car to the RSV; control of propellant temperature; the addition or removal of incremental amounts of propellant to "top" the rocket tanks; return of propellant from the rocket tasks to the RSV; flush and purge of the subsystem.
5	5	1		The maximum number of personnel in the system operating crew will be two.
6	5	1		Because of the nonavailability of experienced personnel, it is required that all tasks with a difficulty index of two or more shall be performed by automatic means.
7	2	4		A maximum of 18 personnel will be available for the operating crew.
8	3	2	1	The subsystem will be operated by Air Force personnel with no prior experience except a three-months course in missile operations

*Subjects were required to indicate whether the individual statement would: (I) Greatly affect design; (II) Slightly affect design; (III) Have no affect on design.

TABLE VIII

RATINGS BY SIX DESIGNERS OF THE INFLUENCE OF VARIOUS TYPES OF PERSONNEL REQUIREMENTS UPON DESIGN

	Number of Responses in Each Category*			Requirement
Item No.	I	II	III	
9	1	5		The subsystem will be operated by Air Force personnel with an AFSC 3 skill level.
10		6		The subsystem will be operated by Air Force personnel with a 7 AFSC skill level.
11	1	2	3	The capability of Air Force personnel to operate the subsystem will be demonstrated over a minimum of 20 operating cycles. No more than one error in each operating cycle will be permitted.
12	1	1	4	The satisfactory condition of all subsystem operations performed by personnel will be verified by one or more monitoring personnel before the next subsystem function can be initiated.
13		1	5	All Air Force personnel who will eventually operate the subsystem will be trained and their capability to perform verified by the contractor before being permitted to operate the subsystem without supervision.
14			6	It is anticipated that phasing out of Titan I operational squadron will make available a supply of personnel trained to operate and maintain the subsystem.

* Subjects were required to indicate whether the individual statement would: (I) Greatly affect design, (II) Slightly affect design; (III) Have no affect on design.

Leaving out the third item in the table (which refers to a cost constraint) as not being relevant to the question, it is apparent that for five of the manpower requirements (Items 1, 2, 4, 5 and 6), at least five of the subjects considered that the potential effect of the requirement, if included in the SOW would be to greatly affect design. Nine of the 13 requirements (Items 1, 2, 4, 5, 6, 7, 8, 9, and 10) were considered by subjects to either greatly or slightly affect design. The other four manpower requirements (Items 11-14) were considered by at least five of the six subjects to have no effect on design. These four requirements were the ones which, when the requirements were developed initially, were deliberately made most general and were phrased in informational terms only; they deal with relatively abstract concepts (e.g., personnel availability, training, etc.).

Are these data the result of pure chance? The answer can be derived by testing the distribution of responses across the three categories by use of the Chi-square statistic.

If these responses occurred by chance, the total number of responses in each category would be 26 (i.e., number of subjects, 6, times number of statements, 13, divided by the number of categories, 3). The distribution of responses in each category is as follows:

	I	II	III
Actual	36	23	19
Expected	26	26	26

It is apparent that one must reject the hypothesis of responses distributing themselves across the three categories by chance at the 5% level. Chi-square equals 6.04, 5.99 being required for significance at the .05 level. One can say then with a fair degree of confidence that when PRD statements are phrased precisely, as requirements, and are relevant to concrete subsystem operations (e.g., Items 1, 2, 4, 5 and 6), they will influence design greatly; on the other hand, when PRD inputs are nonspecific and deal with what to the engineer are relatively abstract concepts, (e.g., Items 11-14), they will have no influence on design.

(9) Overall subsystem design comparisons. Each engineer's subsystem design was evaluated in terms of equipment reliability, human reliability, safety, design adequacy and cost. The comparisons are shown in Table IX.

The first thing one wishes to know is how consistent these evaluations are (e.g., whether the five evaluations correlate significantly with each other).

Kendall's W measure of consistency indicates that the rankings of the various parameters which enter into overall subsystem effectiveness are not significantly consistent ($W = .24$). Certain of the parameters are, however, highly correlated, i.e., equipment reliability, human reliability, and safety. The lack of overall consistency may result from the subjective elements entering into the safety and design adequacy evaluations, or it may be that the various aspects of system effectiveness cannot be combined to form a single measure.

Nevertheless, for the extremes of the design distribution, the agreement among the measures is quite marked. The design (subject H) found to be most reliable from an equipment standpoint is also most reliable from a personnel standpoint and has second ranking from a safety and design adequacy standpoint. Significantly, this design is the most costly (which is quite understandable).

Subject K's design, which is least reliable from an equipment standpoint is rated as least adequately designed and almost as costly as subject H's.

In terms of differences between the two groups, the LS/H# group has a mean equipment reliability of .9648, whereas the HS/L# group has a mean equipment reliability of .9267. Although any statistical test of these differences would be meaningless with an N of 3, it is apparent that if the same range of differences were reflected in a larger group of engineers, the difference between the two groups would be highly significant.

The difference in equipment reliability may be a reflection of the same factors which caused the HS/L# group to incorporate more manual tasks in their subsystem: the fact that they were required to design for a more highly skilled set of operators may have led them to design a less automated subsystem and this in turn produced a lower mean equipment reliability. On the other hand, the greater automation found in the designs of the LS/H# group (a reflection of the fact that they were required

TABLE IX

SUMMARY OF SUBSYSTEM DESIGN COMPARISONS

Subject	Group	Equipment Reliability Value	Equipment Reliability Rank	Human Reliability Value	Human Reliability Rank	System Safety Rank	Design Adequacy Rank	Cost (thousands) Value	Cost (thousands) Rank	Mean Rank
N	LS/H#	.9705	(2)	.9000	(2)	3	4	558	(1)	1.5
S	LS/H#	.9383	(4)	.7300	(5)	3	5	609	(2)	4
H	LS/H#	.9858	(1)	.9139	(1)	2	2	1,198	(6)	1.5
J	HS/L#	.9696	(3)	.9048	(3)	3	1	707	(3)	3
D	HS/L#	.9298	(5)	.4604	(6)	3	3	732	(4)	5
K	HS/L#	.8809	(6)	.8105	(4)	1	6	930	(5)	6

Overall Consistency

W .24 (nonsignificant)

Parameter Correlation

(1) Equipment Reliability - Human Reliability

r_s 3.05, p .01

(2) Equipment Reliability - Safety

r_s 2.53, p .01

(3) Equipment Reliability - Design Adequacy

r_s 0.60, nonsignificant

to design for lesser skilled personnel) could have resulted in higher reliability. This is a point which needs further investigation and is raised here largely as a reasonable hypothesis.

The differences between the two groups in terms of human reliability are even more striking than are those of equipment reliability. The mean human reliability for the LS/H# group was .8479; that of the HS/L# group was .7252. This difference cannot but be highly significant.

If we make the same hypothesis as before, that the LS/H# group automated their designs to compensate for their lesser skilled personnel, then the higher human reliability of this group results from deliberately removing the opportunity for human error by eliminating manual functions. The converse of this would also seem to be reasonable: the lower human reliability of the HS/L# group resulted from the inclusion in their subsystem designs of more manual tasks, thus permitting a greater opportunity for human error.

The human reliability results do suggest the important influence of manpower requirements. These results, however, should not be interpreted to mean that a better subsystem design is automatically produced by eliminating human functions. The human reliability measure is directly responsive to the number of manual tasks only and does not take into account the probability that more highly skilled personnel would be <u>less likely</u> to make errors, even when they had a greater opportunity to do so.

The differences between the two groups in terms of safety are obviously so slight as to be insignificant. The difference in mean ranking for design adequacy between the two groups is also so slight as to be meaningless: 3.3 for the HS/L# group, 3.6 for the LS/H# group. Costs for the subsystems, when distributed by group, are almost identical: the HS/L# group having a mean of $789,000, the LS/H# group having a mean of $788,000.

What do these results imply? Manpower requirements do seem to have an influence on equipment and human reliability, but none on safety, design and cost. One possible reason for the fact that the latter indices failed to differentiate the two groups is that they depend on rather global, subjective rankings which may be comparatively insensitive to fine design variations.

The effect of manpower requirements on system effectiveness measures is, however, probably not direct.

The effect of any set of requirements, whether these be cost, reliability or personnel resources, is filtered through a medium or barrier which

attenuates the influence of those requirements. This medium or barrier is what has been termed in this report the engineer's idiosyncratic "design style." That design style consists of the engineer's interpretation of the initial set of requirements and the established means he has of implementing those requirements through design. If the initial requirements were not modified by the engineer's interpretation of their relative importance, and the means he employs to implement them, their effect on the equipment configuration would probably be greater.

This can be clarified by reference to some individual subject examples. The advantage in mean equipment reliability of group LS/H# was considerably assisted by subject H, whose subsystem had the highest reliability. Why? H's design was that of a completely automated subsystem involving the use of two computers, one for backup. The reason H went to such a design configuration was not particularly that he was influenced by the personnel requirements expressed in the SOW (although the constraint of having lower skilled personnel in his crew may well have reinforced already existent design attitudes within him), but because he viewed the time and reliability requirement in the SOW as more important than any other. He felt he could not meet the time and reliability requirements in any way other than by automation. His interpretation of the severity of the time and reliability requirements was not shared by the other engineers. With his idiosyncratic design style, Subject H proceeded to design a completely automated subsystem with special provisions against the possibility of failure, either of equipment or personnel. Hence, his high reliability and equally high cost.

Other subjects had other design styles. Subject K and several others believed just as strongly in manual as opposed to automatic systems. Subject K also interpreted the high reliability requirement in the SOW as being of top priority, but solved that problem by including redundant components rather than automaticity in his subsystem. K's increased number of components cost him dearly in terms of equipment reliability and almost as much in terms of money.

Attention must, therefore, be drawn to the necessity of clearly explaining the priority to be accorded to design criteria in the SOW. If cost is the essential factor in a subsystem, this must be indicated beyond any shadow of doubt. The same is true of other design criteria. It does not help the procuring activity to get the system it desires to include equivocal statements such as, "The system will be designed to the highest possible reliability commensurate with cost," or "The system shall be designed to minimize the possibility of human error, within cost and reliability limitations." Such vague statements will force the engineer to apply his own design criteria and design strategy which may or may not coincide with those of the procuring agency. Possibly, the procuring activity should apply an ordinal scale of priorities to the several requirements in the SOW. Tradeoffs between cost and reliability, cost and personnel requirements, etc., should be clearly indicated in the SOW.

From the standpoint of personnel requirements, which are "foreign territory" to most design engineers, these requirements must be phrased unequivocably and emphatically. General statements reflecting design goals such as, "The system shall be designed to take maximum advantage of personnel capabilities" are practically meaningless to the design engineer (and even to the personnel specialist). The explication of personnel requirements in the SOW may not completely overcome the effect of the engineer's peculiar design style and strategy, but it will mitigate its effects.

Qualitative Analysis

Another way to determine the effect of personnel requirements on design was to reverse the requirements for the two groups in session 8. Subjects of the LS/H# group arbitrarily had the number of personnel they had assigned themselves cut approximately in half (e.g., from 12 to 6), and the skill level of the reduced crew was substantially increased. Subjects of the HS/L# group had their estimates of the number of personnel available to them increased significantly (e.g., doubled or tripled depending on the original estimate the engineer had made), and the skill level of the new personnel reduced substantially.

These changes in quantitative and qualitative manning produced changes in equipment design, but certain subjects strenuously resisted design modifications. The flavor of the subject responses can be seen in the following:

High Skill/Low # Group

(1) Subject K. He estimated 7; this was upped to 15. This subject felt that the addition of personnel would not compensate for their reduced skill level. In terms of what he would do to modify his design, he indicated he would change his procedures; make them more inflexible, more proceduralized (step by step), with nothing left to the imagination. He might tend to automate more, but felt that cost would negate this.

(2) Subject D. Estimated 8; upped to 15. This subject felt the change was unreasonable but normal for system development. He would make changes only in the control area; would add some displays and would eliminate checklists. He felt that the lowered skill level would require a more automatic system hence he would add more interlocks.

(3) Subject J. Estimated 3; upped to 10. This subject felt that the change in manning would not affect his design, because it was already automatic and the automaticity was required because of the reliability requirement.

Low Skill/High # Group

(1) Subject H. Estimated 9; cut to 6. This subject felt that the change was unreasonable and that he could not maintain the system with the reduced number of personnel. However, he would not change his design configuration.

(2) Subject N. Estimated 4; cut to 2. This subject felt that the system could be operated by two people, but one would have to do away with the "buddy system" (i.e., the requirement that all personnel operations be performed by two men). He would not change the physical design configuration.

(3) Subject S. Estimated 12; cut to 6. This subject would not change his equipment configuration because of the change in skill level. Since he had already designed the equipment for lower skilled people, more skilled personnel would be able to operate it. However, he might modify the mechanical layout of his equipment, i.e., centralize his control functions. He might change his control/display layout to be operated by two people, rather than four. He would also put in a loudspeaker system to facilitate communication.

It is apparent that some of the design engineers strenuously resisted the modified manpower requirements, not only in session 8 but also in debriefing interviews following the individual test sessions. Several conclusions are possible:

(1) Personnel requirements do have some influence on hardware design. However, when they are imposed on an already established design, their effects are not manifested in the basic design concept which remains intact, but on peripheral aspects (e.g., controls and displays, communications, procedures). The implication is that for personnel requirements to have sufficient influence on the basic design concept, they must be provided at or before the time that design concept is developed. This is reinforced by subjects' statements to essentially the same effect.

(2) Once he had created his design, the engineer resists the effect of personnel requirements to the point of denying the obvious need for a redesign. This implies that if the requirement had been specified initially (before the design concept was developed), it would have been accepted more gracefully. In other contexts, this statement was made by a number of engineers.

(3) Engineers do not feel additional personnel compensates for reduced skill level. Thus, four lesser skilled technicians are not considered equivalent to two more highly experienced technicians. Skill is given a higher priority than number in these subjects. Thus, the two more highly skilled technicians might be considered adequate to replace the four lesser skilled technicians, but not vice versa. Hence, the skill parameter appears to be partially independent of the quantity parameter, with skill being considered (within limits, of course) capable of compensating for reduced personnel numbers.

One may also ask how the engineer's manning concept is influenced by manpower requirements. If the differing personnel requirements had any influence on the engineer-subjects, it should have been reflected most immediately in the number of personnel which the subjects estimated would be required to man their completed subsystem designs. In session 4, all subjects were asked to estimate the number of personnel they considered necessary to operate their subsystems. They were asked to make the same estimate also at the conclusion of the study. The table below indicates the manning estimates provided.

HS/L# Group			LS/H# Group		
Number of Personnel			Number of Personnel		
Subject	Original Manning	Final Manning	Subject	Original Manning	Final Manning
1	7	7	1	12	12
2	3	3	2	3	4
3	8	8	3	9	9
Group Mean	6.0	6.0	Group Mean	8.0	8.3

All subjects in the HS/L# group had lower manning estimates than those of the LS/H# group, indicative that these requirements did have some effect on their estimates of the manning required. Unfortunately, the number of subjects in this study is too small to make any meaningful statistical tests of significance.

Also, with the exception of one subject (who has responding to the "buddy" requirement for safety and hence added one man to his original estimate as an afterthought), estimates were remarkably consistent from session 4 to session 10. This suggests two things:

(a) Estimates of manning are developed quite early and are apparently not influenced by the addition of equipment and personnel information.

(b) Manning estimates are developed by the engineer himself, even though he may not verbalize these formally until later in design.

Although subjects were not formally asked for manning estimates until the fourth session, their comments in the first two test sessions showed that subjects had at least a rough concept of the number of personnel and the skill level needed to operate their subsystems. With regard to skill level, all subjects felt that a subsystem with potential hazards in it required highly skilled personnel. Although it was difficult for them to understand the terms in which the Air Force skill level designations are phrased, subjects were acutely aware of the significance of skill for the operation of their subsystems.

One would hope that the manning estimates would be influenced by the QQPRI information provided in session 6. b. The following estimates were provided as part of the PRD input for that session: HS/L# group: 9; LS/H# group: 12.

Note that this input caused no change in the original manning estimates developed by engineers, suggesting two things:

(a) Manning estimates provided downstream in design have no effect on the engineer's manning concept developed earlier.

(b) The design engineer is reluctant to modify his original manning concept.

Presumably the engineer's manning concept should be related to the nature of his subsystem design. This can be investigated by comparing the manning estimates against the type of subsystem design developed. The subsystem designs can be described in terms of the following categories: remote-manual, semiautomated and completely automated, representing an increasing order of automation. Logically, the more automated the design, the fewer operating personnel should be required.

Four designs were classified (by the designers themselves) as remote-manual, one as semiautomated, and one as automated. The manning involved is described below:

Remote-Manual		Semiautomated		Automated	
Subject	Manning	Subject	Manning	Subject	Manning
S**	17	J*	3	H*	9
K*	7				
N**	3				
D*	8				
Mean	7.5				

* - HS/L# Subject

** - LS/H# Subject

As in the previous studies, the present engineer-subjects designed on the basis of very strongly felt experiential stereotypes. For example, one subject "did not believe" in manual systems, while another believed just as strongly that automated systems were "no good." Hence, the choice of a design concept was probably not markedly influenced by the personnel requirements levied on the individual engineer.

It is even more disturbing to find there is little or no correlation between the type of design proposed and the manning indicated by engineers for these designs. The one completely automated design required more personnel than the mean of the group of four engineers who designed manual systems. On the other hand, the semiautomated design required substantially fewer personnel than either the completely automated or manual subsystems.

This suggests very strongly that design engineers have a very inappropriate concept of the manpower required to operate their systems. From this, one can deduce that the services of professionally qualified manpower estimators are required because one cannot rely on the engineer to develop a manning concept appropriate to his subsystem design.

Particular attention should be drawn to the fact that all engineers had great difficulty in understanding the meaning of skill levels phrased in the Air Force's "3, 5, 7-level" terminology. Although such designations are undoubtedly useful for Air Force administrative purposes, they have no meaning for design engineers. At the present time, little is known about the parameters involved in the skill level concept, particularly those aspects which relate to equipment design.

2. Do Personnel Resources Data Inputs Have a Significant Effect on Equipment Design?

Quantitative Analyses

The basic measure here is the comparison between the outputs of the experimental and those of the control subjects (who did not receive the

PRD input during the session in which they provided the output). Control subjects varied from session to session; hence, it is impossible to compare the results of one session with those of another, or to compare overall subsystem designs for control subjects. Results are available on a session-by-session basis only.

Session 1

Inputs:	Statement of work and personnel function flow diagrams.
Design output:	Number of personnel-related functions specified in schematics.
Experimental Subjects:	Mean 5.3
Control	Mean 5.5

Sessions 2-3

Inputs:	(2) Partially completed Requirements Allocation Sheets (RAS). (3) Supplemental equipment information and control/display memorandum.
Design Output:	Number of personnel-related equipment items specified.
Experimental Subjects:	Mean 75.5
Control Subjects:	Mean 39.0

Session 4

Inputs:	Additional equipment information and a preliminary operations task analysis.
Design Output:	Number of control-display hardware items noted.
Experimental Subjects:	Mean 173.7
Control Subjects	Mean 50.0

Session 5

Inputs:	Requirements Allocation Sheets dealing with Preventive Maintenance.
Design Output:	Number of maintenance/test equipment items noted.
Experimental Subjects:	Mean 2.3
Control Subjects:	Mean 1.5

Session 7

Inputs:	Complete QQPRI
Design Output:	Number of operating problems anticipated.
Experimental Subjects:	Mean 8.5
Control Subjects:	Mean 13.5

Again, it must be emphasized that with the small number of subjects available (at each session four experimental and two control subjects) the results can be indicative only. With this qualification it would appear as if certain PRD inputs did have major effects (sessions 2, 3, and 4). Certainly, the number of personnel related equipment and control-display items noted were substantially greater for experimental than for control subjects. The number of maintenance/test equipment items produced by all subjects in session 5 and the number of operating problems anticipated in session 7 were too small to draw any conclusions relative to the hypothesis.

If one associates the type of PRD input with the individual test sessions, it is possible to develop an explanation for some of the conflicts in these results. Sessions 2-4, those with the most significant differences between experimental and control subjects, presented PRD inputs which engineers utilize most readily. These inputs are task performance requirements, personnel/equipment analyses (e.g., control-display memorandum) and preliminary task analysis.

In session 7, which showed a slight reversal between experimental and control subjects, the experimental subjects had received the QQPRI which listed many of the potential operating problems which the designers had been asked to anticipate. It is possible that the engineers in the

experimental group felt that they need only add certain problems to the list already provided in the QQPRI. Since only these additional operating problems could be counted for the experimental-control group comparison, the number of these problems would be less than that produced by the control group.

One may ask how, in view of the engineer's indifference to PRD inputs, some of these inputs could exercise an influence on design outputs. Whatever other specific value these inputs possessed, they were valuable from the standpoint of "prodding" the engineer to consider certain aspects which he had overlooked. For example, the memorandum of control-display requirements may not have caused the designer to buy the particular configuration described in the memorandum, but it caused him to think about the need for controls and displays in general.

Likewise, when maintainability inputs were presented to subjects in session 5, some of the engineers reported that they had completely forgotten up to that point about subsystem maintainability. The new input then required them to modify their design somewhat. Thus, even when it appears as if a particular PRD input has missed its mark because it does not produce an immediate effect in terms of the design change for which it was developed, it serves a useful purpose in reminding the engineer of factors he might otherwise have ignored.

Qualitative Analysis

Results of the debriefing episodes at the conclusion of each test session produced varying responses to the question of PRD utility.

In the first two sessions, all subjects indicated that the PRD provided would not be particularly useful at this stage of design, but that perhaps it would be of more value later in the design process (later on being related to the creation of operating procedures, etc.). In this connection, note that a PRD input was seen as useful when it could be immediately (or eventually) tied to some concrete system design output, such as an operating procedure.

In the third session, subject opinion was split as to the value of PRD. Half the subjects indicated that they still saw no need for PRD, including what was previously available. The other half indicated that they felt some indication of the type and quantity of people as a definite necessity at this design stage.

In later sessions, the utility of PRD inputs did not show significant improvement, particularly because of inappropriate timing. That is, decisions as to the number and location of control panels, for instance, had been made by the individual designer far in advance of the arrival of the memorandum describing human factors recommendations for these items. This tendency of PRD to arrive too late to influence engineering decisions was repeated at every stage of design.

Three of the six subjects were consistently more positive in their reactions to PRD inputs than the remaining three.

An analysis of subject characteristics (e.g., years of experience, educational background, type of job responsibility) does not indicate any particular factor, other than their attitude, which differentiated them from nonreceptive engineers. This suggests that, if the subject sample used in this study are representative of the entire engineering population, there are many more engineers than had been suspected who can be influenced to some degree by personnel resources requirements. It also suggests the need to study engineers in greater detail concerning what can be termed their "design style."

3. At What Stage of Subsystem Development Do Manpower Requirements and Personnel Resources Data Have Their Greatest Effect on Equipment Design?

The consensus of subject opinion with regard to PRD inputs was that they would have considerably greater impact if they were made available either in conjunction with or soon after the SOW. Engineers indicated that specific items of information, such as the number of personnel the subsystem should utilize, recommended controls and displays, etc., would probably have a greater effect on equipment design if they were presented as requirements within the SOW. Throughout the test program, subjects reiterated that in order for PRD inputs to be particularly effective in influencing or changing an already established or about to be established design they must either be provided early enough to act as one of the initiators of the design concept or be a constraint or restriction imposed upon the designer.

4. In What Forms are PRD Inputs Most Effectively Used by Designers?

With regard to the individual PRD inputs, the following can be said:

(1) Statement of work, including definition of skill level and flow diagrams of personnel functions. Because these inputs were purely informational (i.e., not phrased as requirements), they were considered by engineers as having no influence on design. This does not conflict with the statements made immediately above. These inputs would have been effective had they been phrased as requirements and included in the SOW. As purely information data, they were thought to be more appropriate to a later design stage. The reason for this is that engineers typically feel that personnel data as data should be outgrowths of equipment rather than as factors influencing that design; hence, they considered that these inputs should be delayed until that design had been formalized.

(2) Requirements Allocation Sheets with personnel section completed and more detailed diagram of required personnel functions. Subjects interpreted the PRD input as a preliminary operating procedure. They felt that "the design should dictate this (the PRD input) rather than have the PRD control design." Informed that the PRD input was an outgrowth of design rather than a constraint on it, the engineer proceeded to ignore it.

(3) Control-display memorandum. Five of the subjects found the memorandum more or less useful in that they interpreted it as being directive of a certain approach toward controls and displays which the customer wanted taken. The sixth subject rejected the memorandum because it conflicted with the design approach he had adopted.

(4) Preliminary task analysis. Subjects all concurred that the task analysis had some value. Half the subjects indicated that they would not expect to receive this kind of information during design, while the others indicated that they would have to develop this kind of information themselves in the course of design. When questioned as to the elements of the task analysis which were particularly useful, half the subjects indicated that the simple task listing was the most useful; the other indicated that the performance requirements section, e.g., specification of task complexity, communications needed, etc., was the most useful element.

(5) Maintenance analysis (included on Requirements Allocation Sheet). This includes preventive maintenance functions with personnel section of the Requirements Allocation Sheet (RAS) filled out, supplemented by a maintainability checklist. Subject reactions indicated that four of the subjects regarded the information provided as useful and having an impact on the assigned task. They found the data under the task heading on the RAS to be most useful. The other two subjects were not impressed by nor did they find the RAS useful.

Three of the subjects regarded the checklist provided as an extremely useful tool. The other three, however, were not impressed and in one case even opposed the use of the checklist, i.e., it was something a "checker" would use to check a design. Those opposing the checklist indicated that all the elements mentioned in the checklist constituted an integral part of "good design" or good standard practice, and that while the designer may not outwardly mention these things, they are present in the "back of his mind" and the important things would get taken care of.

(6) Time line analyses. There was one each for operations and maintenance functions, and a Preliminary QQPRI (see Glossary) described the qualifications and number of personnel required in the system. Subjects did not view the time-line analysis as particularly helpful, indicating that its informational content merely confirmed their own conception of time sequences in their system. With regard to the QQPRI, all but one of the subjects disagreed with the number of personnel predicted. The only subject agreeing with the QQPRI prediction did so because of the chance coincidence of his prediction with that of the QQPRI. Subjects refused to modify their predictions of the crew sizes they had selected.

(7) Full Scale QQPRI. The existence of the QQPRI had no significant effect on subject performance and only one subject indicated that it was useful. Questioned as to the effect of timing, subject opinion was evenly divided between those who felt it was impossible to develop this level of detail any earlier and those who felt that this type of information would be most useful at the inception of design.

It is obvious from these subject responses that no simple yes or no answer can be provided to the question of utility. Certain inputs do have value: those which describe the operations of the system, such as task information; and those which are interpreted as representing the customer's wishes (e.g., control-display memorandum), thus imposing a design requirement. The directness of the relationship of the input to equipment features is important also: those inputs, such as training requirements, position descriptions, etc., which have only a peripheral relationship to equipment functioning are considered of much less importance than inputs such as lists of tasks.

Additional evidence is available from rankings supplied by subjects in Items 9-2, 9-5, and 10-3 concerning the particular PRD items which are the most useful and have greatest effect on design.

Item 9-2. Subjects were asked to rank the importance of all inputs provided to them during the study. The mean rank assigned to each individual input is shown in Table X. The disparity in responses noted previously is reflected in the subjects' lack of consistency, with Kendall's W statistic (.38) failing to be significant at the .05 level. However, the mean rankings are consistent with other subject mean responses during the test sessions.

As would be expected, the SOW and the additional equipment information provided during the sessions were considered most important. Of

TABLE X

RANKING OF THE IMPORTANCE OF INPUTS PROVIDED DURING THE STUDY

Mean Ranking	Item
1	Statement of Work
2	Additional equipment information
3	Performance requirement on RAS
4	Control-display memorandum
5	Description of tasks
6-7 (tie)	List of personnel tasks
	Task durations
8	Functional flow diagrams for personnel functions
9	Number of personnel available
10	Difficulty index
11	Kinds of personnel available
12	Probability of successful task completion
13	Time-line analysis
14	Training requirements

the PRD inputs, the most important are those which are equipment-oriented in terms of the operations needed to be performed. Task information which cannot be readily related to equipment operations is considered of little importance.

Upon completion of the ranking task, subjects were questioned as to the utility of the information contained in the input, the impact of that information upon his design (if any), and the sequencing of the input.

Item 9-5. Subject's rankings of the relative value to be placed upon items which might appear in a statement of work (SOW) are summarized in Table XI. Those items were presented to subjects as they might appear in a SOW for the design of a PTPS to be manned by Air Force technicians about whom the design engineer knew nothing.

As before, those items which are restrictive are given higher priority than those which are essentially informational in nature. Cost and physical equipment parameters rank higher than any behavioral parameters. However, the sequence of task operations and the maximum number of personnel permitted in the crew take fourth place. Skill and difficulty level descriptions, human error probabilities and training details are considered relatively of little value. Kendall's W statistic indicates that subjects are fairly consistent in their responses to this item. W = .61, which is significant at the .05 level.

Item 10-3. In Item 10-3, subjects were asked to rank the items of information they might want to know in order to develop an appropriate design for a PTPS system to be operated by only two men. The underlying hypothesis was that the extreme restrictions on the number of personnel to operate the system might cause subjects to change the order of priority of the various informational parameters available to them, in other words, to emphasize more information items relative to personnel. The results of the ranking is shown in Table XII. Subject responses are consistent, as measured by Kendall's W, at the .05 level (.51).

Despite the severity of the personnel requirement, apparently the engineer still structures his design analysis first in terms of the physical parameters describing the system. Thus, the first four items ranked all relate to the physical parameters of the system configuration. It is only after this that parameters which we would consider to be personnel-related (e.g., sequence of task operations, concurrent task, skill level, etc.) are considered. As before, training, human error probabilities, and personnel availability are considered of relatively little importance because of their more abstract nature.

TABLE XI

IMPORTANCE OF ITEMS IN THE STATEMENT OF WORK

Mean Rank	Item
1	Cost restrictions, if any
2	Customer's philosophy with regard to subsystem automation
3	Physical configuration of the site on which the PTPS is to be located
4	The maximum number of men you will be permitted to have in each crew
4	Sequence of task operations
5	Lists of tasks to be performed by each crew member
6	Criticality of each task to be performed, in terms of consequences to system performance and safety
7	Identification of which tasks must be performed concurrently
8	Number of personnel required to perform each task
9	Description of the experience background which crew members must have
10	Air Force skill level designators of system personnel
11	Difficulty associated with each task
12	Probability of human error in performing tasks
13	Details of the training which will be provided to the Air Force technicians
14	Availability of personnel within the Air Force to become PTPS operators

TABLE XII

ITEMS OF INFORMATION OF IMPORTANCE IN THE DESIGN OF THE TWO-MAN PTPS

Mean Rank	Item
1	Manner in which fuel will be transported to the RSV
2	Type of fuel to be transferred
3	Physical configuration of the site on which the PTPS is to be located
4	Required performance reliability of the system
5	Sequence of task operations
6	Identification of which tasks must be performed concurrently
7	The speed with which each individual task must be performed
8	Latest information about process control equipment
9	Air Force skill level designation of prospective personnel
10	Education background to be required of prospective personnel
11	The number of displays which can be accurately monitored by one man at the same time
12	Criticality to system operation of individual tasks
13	Analysis of which tasks should be performed by personnel
14	Electrical power requirements

TABLE XII (concluded)

ITEMS OF INFORMATION OF IMPORTANCE
IN THE DESIGN OF THE TWO-MAN PTPS

Mean Rank	Item
15	Analysis of the types of human errors which might occur in operation
16	Probability of human error in performing individual tasks
17	Description of the training to be given to personnel
18	Availability of personnel within the Air Force to become PTPS operators
19	Speed with which personnel in protective clothing can react
20	Average reach distance of Air Force personnel

5. What is the Design Engineer's Concept of Human Factors in Systems Design and His Attitude Toward PRD Inputs?

Little more can be added to what has been described previously. The attitudinal problem as it affects the use of PRD inputs is probably the most severe one of the complex of factors which militate against the engineer's use of those inputs.

The acceptability of an input is determined to a great extent by its source. One can think of an input as emanating from a higher level (e.g., customer, company management), from a level parallel to the designer (e.g., an engineering group recognized by the engineer as having a technical capability equal to his own), or from a lower level (e.g., from a group which is not part of engineering or which does not have status equal to the designer's.

An input stemming from a higher level is ordinarily accepted as "gospel"; undoubtedly, this is related to the engineer's perception of the input as imposing a design requirement. He may consider the input as idiotic, but he will comply, provided he has no other recourse. Lateral inputs (e.g., from a level parallel to that of the engineer's) are reviewed and accepted if they fit into the designer's concept or are considered technically correct (i.e., cannot be successfully attacked). Inputs from a lower level (a human factors group is often in this attitudinal category) are usually rejected or accepted only after much resistance.

The engineer is very critical of anything which he considers to be technically incorrect. Vague inputs (i.e., phrased in generalities) offend his sense of precision and concreteness. The engineer requires that the input be specific, spelled out in detail, as well as being practical; consequently, the personnel specialist may have to demonstrate the practicality of his recommendations. Finally, the input has to tell the engineer something he has not thought of before or something he has not fully thought out until now. All of this can be summed up by saying that if the personnel specialist is accepted by the engineer as an equal (i.e., as technically competent), what he has to say about the engineer's design will be accepted at face value.

6. How Does the Manner in Which the Engineer Designs Affect the Utilization of PRD Inputs?

The most surprising finding relative to the manner in which the engineer designs was the speed with which he proceeded to definitize his subsystem configuration.

It has been assumed that the development of equipment details would be preceded by the following analytic stages:

(1) Determination of system/equipment functions

(2) The allocation of functions between equipment and personnel

(3) The specification of equipment design requirements (as distinct from system requirements)

(4) The interrelationship between equipment functions

(5) The specification of equipment characteristics to satisfy equipment requirements and functions

Sessions 1 through 4 were deliberately devised to permit the engineer to reveal these analytic processes overtly. The experimental approach was specifically modeled on the system analytic steps listed above, and explicitly called for the subjects to make analytical decisions in accordance with this process. For example, the first session required the subject to detail system functions and subfunctions; the second session asked him to detail equipment functions and subfunctions; and the third session asked him to specify equipments needed to implement these functions, etc.

To the investigator's surprise, all subjects in the first session responded by producing a detailed schematic diagram which included the following features:

(1) Explicit equipments needed, e.g., heat exchanger

(2) Piping lines between equipments and even geographical (site) arrangements

(3) Valving required to operate the equipment

(4) Determination of which valves would be remotely and which manually operated

(5) Equipment tolerances

(6) Some indication of crew size and composition

Figures 12 and 13 in Appendix III show the level of detail produced in the first session.

In the very first session, subjects had developed a complete design concept; and subsequent sessions merely enabled them to refine the

concept, but only in a very molecular manner (e.g., addition/deletion of individual valves, etc.). Under these circumstances, almost all of the PRD inputs provided were late, in the sense that the basic design decisions to which they had relevance had already been determined. Once such decisions are made by the engineer, they are almost impossible to change, as seen by the response of the subjects to the changed personnel requirements in session 8.

Under these circumstances, if PRD analyses and inputs are to have any effect on design, they must be available at the very start of design. This may appear to be at variance with the comments of some subjects, when they indicated that such PRD inputs were too early, or should be provided only later, or would be of greater value later in design. The contradiction is explained by the fact, pointed out previously, that engineers typically think of personnel inputs as relating to molecular, "knobs and dials" characteristics of the equipment which are handled later on in design.

Evidence with regard to the criteria which the engineer applies to his designs is presented in Table XIII. In Item 9-1, engineers were asked to rank the relative importance of various parameters to their design and the degree to which they should influence the designer. The same test item had been administered to the two groups of engineers tested in the previous studies (BR - Bunker-Ramo, DAC - Douglas Aircraft). It was administered to the present subjects to determine whether the present engineer-subjects approached design with the same attitudes as previous subjects. To the extent that they did, it would permit one to combine the findings of the previous studies with those of the present one. In addition, it was of interest to determine the relative priority assigned to the various considerations that may enter into the designer's analysis of his design problem.

Responses of the six subjects were fairly consistent when measured with Kendall's W, being significant (.38) at the .05 level. The Spearman rank order correlation coefficient was applied to determine the consistency of Marquardt (TMC) subjects with BRC and DAC subjects.

The correlations between TMC and BR, and between TMC and DAC subjects are significant at the .05 level or better. As with all other indices of design style noted previously, the present subjects are concerned primarily with physical parameters, equipment characteristics, cost and reliability. The importance of personnel factors is relatively low on the scale.

It seems reasonable to assume, therefore, that the present subjects are highly representative of engineering population as a whole.

TABLE XIII

RELATIVE IMPORTANCE OF DESIGN PARAMETERS

Rank			
TMC	DAC	B-R	Design Parameters
1	4	1	The physical characteristics of the environment (e.g., temperature and vibration) which the equipment must tolerate.
2	5	2	The reliability required of the equipment (e.g., 150 hours MTBF).
3	2	3	Characteristics of the equipment (e.g., type of component, its operating mode, and the way in which internal components must be mounted).
4	6	8	The relative cost of components to be selected for use in the equipment.
5	3	5	The complexity of equipment operating procedures.
6	1	4	The effect of equipment characteristics on the ease with which personnel operate and maintain the equipment.
7	9	7	The accessibility of internal equipment components to maintenance personnel.
8	7	6	The ease with which equipment can be manufactured.
9	8	9	The manner in which the equipment should be calibrated and maintained.

Rank correlation between TMC and DAC groups .90, p .05
Rank correlation between TMC and BR groups .97, p .05
Rank correlation between DAC and BR groups .75, p .01

7. How Available is Information as a Whole to the Engineer During Design?

In general, engineers receive less information than they would prefer to have. On the other hand, their attitude toward that information is highly significant.

Depending on the engineer's design style, he either welcomes as much information as possible as early as possible, or views information as potentially constraining his freedom to design creatively. The former would be willing to accept PRD inputs even if they did not use them. The latter would vehemently refuse even to accept such inputs. One subject had to be replaced after the initial session, because he considered that the personnel inputs for session 2 were so detailed as to demean him (e.g., "an experienced designer doesn't need all this (word deleted) information; if you have to tell an engineer all these things, you may as well get someone off the street," etc.

B. CONCLUSIONS

The major conclusions one can derive from this study are summarized below:

(1) Manpower requirements and personnel resources data inputs do have an influence on the equipment configuration, but this influence is attenuated by a complex of factors such as the engineer's indifference to and inability to interpret human factors considerations meaningfully; and more importantly, by the inadequate timing of PRD inputs.

(2) The potential influence of personnel requirements and PRD inputs on the equipment configuration is much greater than is presently achieved. PRD inputs would exercise much greater effect if they were

(a) Phrased as specific design requirements and constraints and included in the SOW;

(b) Phrased in concrete design-relevant terms.

(3) The manner in which the engineer designs has a significant effect upon his reaction to personnel requirements and his use of PRD inputs, hence on their influence on the subsystem configuration. The engineer's design concept is so quickly developed on the basis of experiential stereotypes (design style) that traditional timing of MR and PRD inputs lag that concept. The engineer resists any change to his initial design concept as a restriction on his freedom to design creatively.

(4) The importance of supplying meaningful manpower information as design requirements in the SOW and subsequent QQPRI analyses by trained Human Factors personnel is highlighted by the fact that the engineer's manning concept does for his own design not appear to correspond to the needs of his subsystem designs.

(5) The results of this study are in accordance with those of previous design engineering studies. This increases the confidence one can feel in the conclusions derived.

SECTION IV

RECOMMENDATIONS

The fact is that the engineer, relying heavily on his past experience, develops his hardware configuration soon after he receives his Request for Proposal (RFP) and design statement of work (SOW). This means that almost all manpower requirements and personnel resources data inputs provided after this point in time will lag that hardware configuration and the decisions which entered into the design concept. Presently, these inputs are supplied by Human Factors personnel progressively during the contractor's design of the system. If what has been found in this study can be relied on, this incremental development of PRD has only marginal utility to the engineer and little impact upon his design.

There is independent evidence for the engineer's extremely rapid creation of the design concept and his excessive reliance on experience as a substitute for systematic analysis of the design problem. Tessmer (1967) analyzed a number of actual system development case histories to determine the criteria used for systems tradeoffs. He found that "in practice, most tradeoff areas are identified and tentative decisions made during <u>preproposal and proposal efforts</u> (emphasis supplied by the authors). These decisions are solidified or modified within the first few months after contract award. It is remarkable that so many tradeoffs are typically resolved in so short a time. A key factor is engineering experience... There is an aspect associated with extensive experience which should be recognized. The possibility exists for excessive "design by decision" with too few detailed studies of areas which should, in fact, be thoroughly investigated. Sometimes the correct decisions are made, but this seems attributable to good luck..as well as experience" (p. 3-3).

It would seem then that manpower requirements and PRD must be available to the design engineer at the time the RFP and design SOW are supplied to him. PRD inputs should be included in the RFP and SOW as design requirements.

In order to accomplish this, however, certain analyses must be performed, either by the Air Force or under contract to it, which will permit the specification of the necessary personnel inputs as timely design requirements.

Until now, these analyses have (with only a few exceptions) been delegated by Air Force System Project Offices to the contractor to be performed as part of the normal system development process. The engineer is consequently presented with not or at least only very gross manpower requirements as part of his initial design criteria. This has led to the present situation in which systems are developed without adequate consideration of personnel inputs.

It is, therefore, recommended that the Air Force, not the hardware development contractor, should perform the initial and basic personnel analyses and determine manpower requirements for systems under development; that the Air Force, not the hardware contractor, should specify the manning structure for the new system; that the Air Force should impose that manning structure on the hardware contractor as a design requirement; and that the contractor should be forced to implement that requirement in his design. None of this is done at present.

Since PRD presently has so little effect on the hardware aspects of subsystem design, it is obvious that the present method of managing personnel subsystem development is severly lacking. The management methodology described in AFSCM 375-5 does not do what it is supposed to do. Its actual implementation by the Air Force fails even to agree with the very regulations (e.g., AFSCM 375-5, AFR 30-8) set up by the Air Force to develop the personnel subsystem.

The management methodology described in AFSCM 375-5 requires that during the System Concept and Feasibility stage of system development (see Figure 1, p. 31) Air Force human factors specialists should perform analyses of human performance and personnel requirements of the system to be developed.

During the Conceptual Transition Phase, a human factors specialist is supposed to be detailed to the System Project Office (SPO) and is supposed to participate effectively in the identification and analysis of system functions.

By the end of the Conceptual stage, Air Force human factors specialists are assumed to be in a position to specify preliminary human performance requirements and identify unique personnel and training problems.

Personnel subsystem inputs to the Preliminary Technical Development Plan (PTDP) including human performance, personnel and training requirements, are supposed to become part of the RFP for Phase 1B of the Definition stage.

The amount of human factors participation in developmental studies performed during the above precontractor phases is minimal. The analyses which AFSCM 375-5 had intended to be performed by Air Force specialists are ordinarily delegated to contractor personnel in later development phases. Since the contractor is eager to arrive at a hardware configuration as soon as possible, the necessary personnel resources analyses are either not performed at all, or if performed, are hopelessly late.

Since the problem is one of management of the personnel subsystem and timing of inputs, it cannot be solved by purely technical means, such as developing a "new" task analysis methodology or a "new" reporting form.

What must be done:

(1) The analyses which AFSCM 375-5 requires be performed by Human Factors specialists in the phases prior to issuance of an RFP must be performed by Human Factors specialists in the spirit of, if not to the letter of AFSCM 375-5.

(2) The results of these analyses in the form of at least a preliminary manning structure must be included in the RFP as a firm design requirement.

(3) The contractor proposing to develop a particular system must include in his proposal an analysis of the effect of that manning structure on his hardware configuration.

(4) The selection of the winning contractor must be based partially on his ability to design hardware in accordance with that manning structure.

(5) The SOW handed to the selected contractor must include the manning structure as a firm design requirement.

(6) The contractor's Human Factors specialists must have as their major responsibility the task of interpreting the manning structure to engineers in design-relevant terms and of insuring that the equipment configuration developed incorporates that manning structure as a basic element.

(7) During contractor development of the system, SPO representatives must monitor design activities more intensively than they have done in the past to "encourage" company management to "allow" the participation of Human Factors specialists in the design process.

(8) The contractor should be required to demonstrate that he has included personnel considerations in his design of the system.

Part of the problem is that until now personnel data have been used to predict and describe what the manning structure should be based on in the hardware configuration. Since personnel inputs produced under such an orientation have had minimal influence upon system design, it is necessary to consider a new concept of system management of personnel subsystem development. This concept has been called Human Resources Engineering (see Eckstrand et al. 1967).

The essence of this concept is that human resources data (i. e., manpower requirements, personnel resources data inputs) must be used as a control parameter during system design to bring the equipment configuration into greater compatibility with the desired manning structure. Human Resources Engineering (HRE) conceives of personnel inputs as influencing the total system configuration (including hardware) in the same way, although perhaps not the same extent, as do equipment inputs.

This requires not so much a change in procedure as it does a change in implementation. In general, the methodology required to exercise HRE control over equipment design does not differ greatly from that presently required for the development of personnel data. The new concept assumes, however, that the methodology which AFSCM 375-5 requires will be fully implemented and that it will be directed at influencing not only the personnel subsystem but also the equipment subsystem.

It may be objected that the required personnel and human performance analyses cannot be performed prior to issuance of the RFP because of lack of data and that consequently a definitive manning structure cannot be provided to the contractor. This is merely an excuse.

While it may appear as if at very early stages comparatively little system information is available, it is possible for the PS engineer to make many deductions concerning personnel requirements based on even a small amount of information. Knowing the general class of system reveals much about the kind of equipment and personnel functions to be performed. Few systems in development are complete technological innovations without any similarity to systems that have preceded it. (If this were so, engineers could no longer design as rapidly as they do.) The data available from predecessor systems can be used to arrive at valuable conclusions.

Note that the system engineer starts his analyses with little more information about the prospective system than the PS engineer has.

It should, therefore, be possible to derive from that initial information a preliminary mission/event analysis, the functions and tasks (to a certain level of detail) to be performed by personnel during the mission, who should perform these, the number of personnel needed to perform the mission sequence, the skills required, etc.

In the performance of this analysis, the Air Force Human Factors specialist will find it necessary to participate in system development in a very vigorous manner, since military engineering personnel, like their contractor counterparts, may be largely unaware of or indifferent to human factors.

Outputs of the personnel analysis must be included in the personnel section of the PTDP. Human resources requirements at a level of specificity equivalent to that of equipment description must be included in the PTDP to insure proper consideration of these requirements by the hardware designer.

The RFP and SOW must also include the following:

(a) Description of the manning structure which the detailed equipment design will fit. Requirements must be specified for:

(1) Maximum number of operating/maintenance personnel to be included in the crew by job position. Such a maximum number for system personnel constrains design by specifying that any system configuration requiring personnel in addition to that number will be unsatisfactory. Job positions, when these are described in terms of Air Force positions, should be referenced to the closest civilian equivalent.

(2) Functions and tasks to be performed and their interrelationships. Although the term "manning structure" usually implies only numbers of personnel and very general descriptions of job positions and skill level, the term as used in this report implies a detailed description of system operations as these are performed by personnel or influence their performance. Since the designer is oriented toward specific operations, function and task description should be phrased in terms of events to be performed in the system mission.

(3) The skill level required for each job position. In describing skill level to the hardware designer, it is essential that this level be related to the specific tasks to be performed by personnel in that system. In addition, the degree of skill required should be described in terms of the amount of supervision required to perform the job.

(4) Length (e.g., three months) and type of training (in terms of capability to perform specific system operations) must also be specified.

(b) Backup data in terms of detailed mission/event analyses and time line plots should be supplied in the form of an appendix to the RFP.

The potential contractor should be required to specify the effect of these requirements in terms of the hardware design concept he is proposing and to indicate alternative design configurations that will satisfy these

requirements. He must indicate the impact of the requirements in terms of expected system performance, reliability, cost and safety. Where it is impossible for him to design to personnel requirements he should indicate why and how, in his opinion, the preliminary manning structure should be revised.

The PS information to be included in the winning contractor's SOW should include the same requirements included in the RFP. However, it should be possible to make these requirements more specific, since the contractor has included in his response details of the anticipated system configuration which can be applied to refine the PS requirements. For this reason, the original RFP requirements should be re-examined by the SPO in terms of the winning contractor's response. Descriptions of functions, tasks and skill level characteristics can be made more detailed by phrasing them in terms of the contractor's anticipated system configuration.

The implementation of such a program will, of course, generate opposition from contractors. The cry will arise, reminiscent of some comments by subjects, that the engineer's freedom to design creatively is being abridged. Such objections are invalid, since the amount of creativity in the engineer's design is limited by his reliance on experiential stereotypes.

These recommendations will, of course, work only if the Air Force personnel specialists analyzing system requirements prior to the issuance of an RFP are highly qualified, if they have time to analyze that requirement not only in human factors terms, but also in terms of their hardware consequences and their interaction with cost and schedule, and if they do not become bogged down in paper work. Naturally, stringent personnel requirements should be imposed only on systems which will operationally stress system personnel.

The implementation of this program will also require a substantial increase in the number of Air Force personnel specialists and their assignment to SPO offices. The Air Force must be sufficiently convinced of the necessity for incorporating personnel requirements into design to spend the money needed to actually do the job and to provide the authority to insure that the job gets done.

During Phase IB (contractor definition), personnel subsystem activities performed in the contractor's facility must emphasize the interpretation of PRD in design-relevant terms.

Because the RFP and the SOW contain firm requirements describing the new system's manning structure, the role of the contractor's PS engineer during development must change from what it has been. Presently, the contractor's PS engineer spends most of his time attempting

to predict a manning structure which is implicit in an already established equipment configuration. The result is that his efforts dissipate themselves in largely useless paper work.

Under the new HRE concept, since the desired manning structure has already been specified in the RFP and SOW, it should no longer be necessary to perform these analyses. Rather the emphasis must shift to:

(1) Interpretation of the manning structure requirements in terms of what they mean for equipment design.

(2) Performance of further analyses to determine more detailed personnel requirements.

(3) Analysis to determine that the detailed elements of the design configuration (e.g., controls and displays, work place layout, etc.) are compatible with the detailed personnel requirements.

All of this means that the contractor's Human Factors engineer will have to become more intimately involved with the hardware aspects of the man-machine interface and participate more vigorously in the design process. He must become more concerned about such things as the number and type of controls and displays, the procedures system personnel must perform, the amount and type of feedback, communication, performance job aids, etc. All of these must be considered in terms of whether they permit the specified number of personnel with particular levels of skill and training to perform efficiently.

The individual PRD inputs, the information they should provide, and how this information should be presented is described in a series of exhibits in Appendix IV.

During this development effort, SPO representatives can make a major contribution to the efficiency of the contractor's personnel analyses by "showing the flag," as it were. Periodic inspection visits, conferences and monthly HRE progress reports from the contractor to the SPO can do much to focus attention on the importance of personnel-related activities. Since it is unlikely that anything other than a major educational effort will change the engineer's deep-seated indifference to personnel factors, the next best solution is to endow these factors with the aura of authority.

A good deal depends on the quality of the Air Force and contractor personnel subsystem specialists. Their competency in interpreting behavioral requirements to engineers is an indispensable factor in arriving at a solution.

The recommendations made in this report cannot be implemented overnight. In the meantime, much more needs to be done in the way of research to provide the Human Factors specialist with the tools that will permit him to translate behavioral requirements into hardware equivalents.

Two areas of research are most important. These are:

(1) Determination of the information required in order to perform the pre-RFP analyses needed to specify detailed manpower requirements in the RFP

(2) Determination of those skill level parameters which are meaningful for design and translation of these parameters into engineering design-relevant terms.

The pre-RFP analyses needed to specify manpower requirements have generally been phrased in some variation of the function/task analysis methodology described by Van Cott and Altman (1956) and Rabideau et al. (1961). This methodology is excessively vague. Moreover, it has never been validated with reference to the very early (i.e., pre-RFP) system development phases in which it is presumed to be utilized. One reason for the Air Force's failure to perform the needed manpower analyses in these early developmental phases may be the difficulty of applying the function/task analysis methodology in these phases.

Specifically, therefore, it is recommended that an empirical study be performed in which the following questions would be answered:

(1) What kinds of information are needed by the system engineer and the Human Factors specialist in order to develop manpower requirements information in this early period?

(2) What kinds of deductions leading to the determination of manning structures can be made from very early system information?

(3) How should these manpower analyses be performed in the pre-RFP period?

The present study has also demonstrated the need for translating Air Force skill level descriptions into terms which are relevant to the design engineer. Present skill level parameters (e.g., capability difficulty, error rate) are oriented around behavioral concepts which do not easily translate into design equivalents. It is, therefore, suggested that skill level be analyzed with the aim of determining (1) how does the engineer conceptualize skill parameters and the skill continuum (i.e., how does he differentiate classes of skill capability)? (2) how do

the engineer's skill level parameters relate to those desired in behavioral terms? and (3) which of these parameters, phrased in equipment-oriented terms, will exercise a significant influence on equipment design?

More generally, we would like to press for more empirical research on the design engineer, particularly with regard to his characteristic ways of attacking design problems. The design engineer is a focal point--perhaps the most important one--of our technology. Despite this and the previous research performed by the authors, very little is known about him. Much more needs to be known. This, of course, is where all research leads: to the need for more research.

APPENDIX I

ABBREVIATED SCENARIO OF EQUIPMENT AND PERSONNEL INPUTS PROVIDED TO ENGINEER-SUBJECTS

NOTE TO THE READER

The length of some of the equipment and personnel inputs provided to engineer-subjects in this study is so extensive that to have included all inputs in their entirety would have made this report extremely unwieldy. Consequently, less important inputs have been compressed by reproducing only that material which is illustrative of the general character of the input. Where an input has been compressed, it has been so indicated by brackets, [ ]. Inputs considered by the authors to be of major importance have been reproduced in their entirety.

Where the purpose of a particular input or part of an input may have been unclear without additional explanation, explanatory material has been added in brackets.

INTRODUCTORY SESSION

Instructions for Participating Engineers

The United States Air Force, through a contract with The Bunker-Ramo Corporation, is conducting a study to determine how engineers make use of the information they are given (or develop themselves) to design a subsystem. Since any subsystem is composed of two basic elements, equipment and people, we assume that the engineer has available to him two kinds of information: information about equipment requirements, characteristics, functions, etc.; and information about or relevant to the personnel who will operate and maintain that equipment.

The Air Force is interested in the engineer's use of both types of information, but it is particularly interested in the use made of personnel information. The reason is that although the engineer is accustomed by training and experience to using equipment information, personnel information is relatively unfamiliar to him. The Air Force is interested in finding out if the personnel information it supplies to the engineer is used by him, and especially if that information makes a difference to the overall subsystem design.

To answer these questions, it is necessary to present this information in the context of the development of some subsystem. Short of actually conducting the study during the development of actual equipment, which would take an excessive length of time, the only other way of creating a developmental/design context was to reproduce or simulate the development of a subsystem in a highly abbreviated form. This

simulation will naturally have to be of the paper and pencil variety. However, this does not concern us too much since we are interested in studying the very early design phases, before detailed drawings are made and equipment fabricated.

What we have done is to take an already developed (operational) subsystem, extract the items of information used in its development and arrange them in a sequence which corresponds to the way in which they were actually used to design that subsystem. The subsystem selected by the Air Force is the propellant loading subsystem for a liquid fueled two stage missile. The reason you were selected as subjects for this study is because you have helped to design similar subsystems.

Obviously, such a propellant transfer subsystem is a very large one, and it would be impractical to ask you to try to redesign the entire subsystem. What we have done is to select only one function of that subsystem - fueling. In addition, we have arbitrarily simplified the subsystem by ignoring many equipments and operations which you, who are experienced in the design of such subsystems, will obviously note. Do not be disturbed by this. The subsystem is supposed only to represent propellant subsystems in general.

The general manner in which we will work is like this. [Description of test procedure follows.]

One thing I should emphasize. The questions we ask and the tasks we ask you to perform are not tests in the conventional sense of the word. The word "test" suggests that only one correct response can be made to these design problems. In these design problems there are no correct or incorrect answers, because only you can tell us what the correct answer should be. For this reason it is most important that, although we cannot completely provide all the conditions under which you ordinarily design, you respond to these problems in the way in which you would ordinarily solve an actual design problem. Remember that the value of the information you provide depends on how accurately it reflects the way you ordinarily design on the job. Remember also that this is not a test of your ability, although we want you to do your best. We would not have selected you to do this work if we did not think you could do it.

We will probably meet once a week and the schedule will be adapted to your convenience. Between our sessions you may, if you wish, refer to the inputs you have been given. However, this part of the study is purely voluntary. During your sessions and in the interim, you may consult anyone in-plant from whom you wish additional information. We do ask one thing of you, however; do not confer with your fellow participants in the study on any aspect of the study. To do so would seriously

reduce the value of the results.

Are there any questions?

Here is the Statement of Work which you as the project engineer for the PTPS will have to design to. We would like you to take it with you and to examine it carefully. Please bring it with you when you return for the first session.

STATEMENT OF WORK

PROPELLANT TRANSFER AND PRESSURIZATION SYSTEM (PTPS)

1.0 PURPOSE AND SCOPE

1.1 Purpose

This Statement of Work (SOW) establishes the requirements for the conceptual design of a propellant transfer and pressurization subsystem (PTPS), including any peculiar handling, checkout, maintenance and instrumentation equipment required. The PTPS is to be used as an integral part of the Titan X Space Launch Vehicle (SLV). The Titan X SLV, which is a two-stage liquid-fueled rocket vehicle, will provide the Air Force with the capability of lifting both manned and unmanned systems into either an earth or lunar orbit. The SLV itself is currently being designed to be launched from fixed surface launchers already available at Vandenberg AFB.

The PTPS to be designed will provide facilities for receiving propellants from GFE railroad cars, for transferring fuel from these cars to ready storage vessels (RSV), for storing the propellants in the RSV for a period of 30 days, and for transferring the stored propellants to the SLV tanks. The propellant to be transferred will consist of a 50% mixture of hydrazine and unsymmetrical dimethylhydrazine. Because of the highly volatile nature of these chemicals, provisions for safety of personnel and equipment will have the highest design priority.

The contractor will note that no provisions have been included in the SOW for work beyond the conceptual design stage (phases 1A and 1B). The government intends to negotiate a follow-on contract for test and production of the PTPS subsystem based on an evaluation of the effectiveness of the designs provided at the conclusion of the present contract.

1.2 Scope

The contractor will design and develop a system having the following capabilities:

1. To provide a capability of receiving propellants from transport vehicles and to store them in storage tanks.

2. To provide a capability for transferring propellants into either of the missile propellant tanks and to return the propellants to the storage tanks.

3. To perform (2) above while accurately measuring the amount of propellants being transferred and while controlling propellant temperature.

4. To add or remove incremental amounts of propellants from Stage I or Stage II missile tanks in order to optimize the load under changing temperature conditions.

5. To provide a means of distributing nitrogen within the PTPS to provide blanket pressure and to purge the system.

Figures 1A and 2A present functional flow diagrams of basic PTPS functions. These describe only fueling functions, since oxidizer functions are essentially identical.

2.0 APPLICABLE DOCUMENTS

General - The following documents form a part of this specification to the extent specified herein. In the event of conflict between the requirements of this specification and any document referenced herein, the requirements of this specification shall govern.

Specifications

Military

MIL-N-6011	- Nitrogen, Liquid and Gas
MIL-P-26539	- Propellant, Nitrogen Tetroxide
MIL-P-27401	- Propellant, Nitrogen Pressurizing
MIL-P-27402	- Propellant, Hydrazine - Unsymmetrical Dimethylhydrazine
MIL-D-1000 1 Mar 65	- Military Specification, Drawings, Engineering and Associated Lists
MIL-M-26512 13 Dec 63	- Maintainability Requirements for Aerospace Systems and Equipment
MIL-H-27894 9 Jan 63	- Human Engineering Requirements for Aerospace Systems and Equipment

Standards

ASME Boiler and Pressure Code	- Section VIII Construction of Unfired Pressure Vessels, Current Edition

Figure 2

Propellant Transfer & Pressurization Subsystem
Top Level Functions

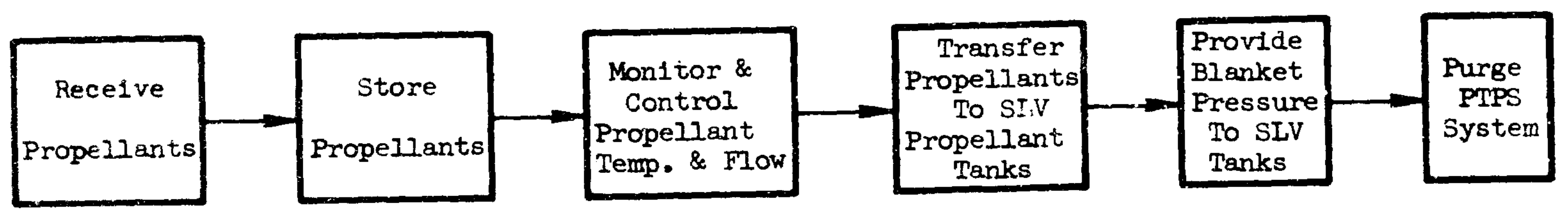
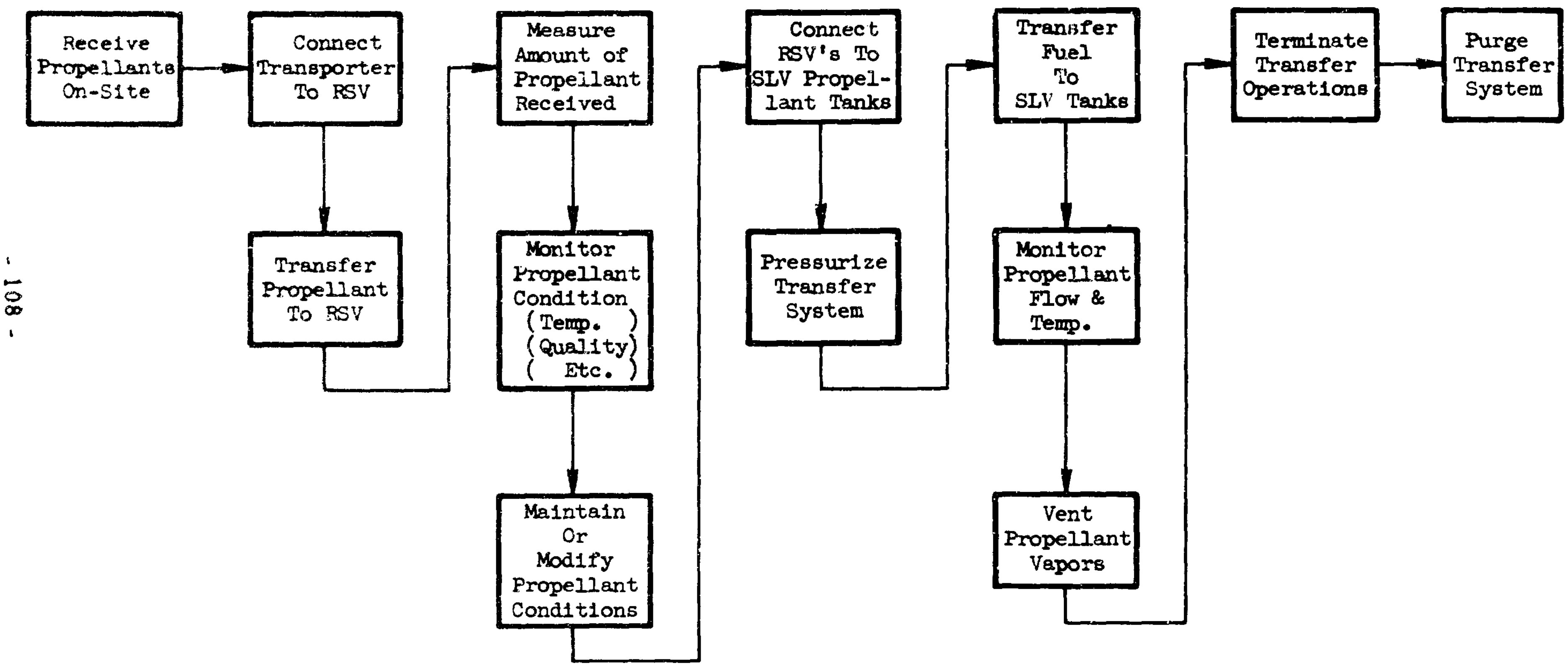


Figure 3

PTPS Second Level Functions



MIL-STD-803A1	- Human Engineering Design Criteria for Aerospace Systems and Equipment. Part 1 Aerospace System Ground Equipment
AFTO 11C-1-6	- General Safety Precautions for Missile Liquid Propellants
MIL-STD-210A 2 Aug 57	- Climate Extremes for Military Equipment
MIL-STD-721 2 Aug 62	- Definitions for Reliability Engineering
MIL-STD-756 15 May 63	- Reliability Predictions
MIL-STD-778 9 Apr 64	- Terms and Definitions of Maintainability
MIL-STD-785 30 Jun 65	- Requirements for Reliability Programs (for Systems and Equipments)

2.1 Other Publications

The following documents form a part of this specification to the extent specified herein. The issue in effect on date of this SOW shall apply.

AFSCM 80-3	- Handbook of Instructions for Aerospace Personnel Subsystem Designers
MIL-HDBK-217	- Reliability Stress and Failure Rate Data for Electronic Equipment
AFSCM 375-1 1 Jun 64	- Configuration Management during Definition and Acquisition Phases
AFSCM/AFLCM 310-1 15 Mar 64	- Management of Contractor Data and Reports

3.0 ENGINEERING INSPECTIONS

3.1 Preliminary Design Review

The contractor shall conduct a preliminary design review not later than 60 days subsequent to award of contract. This review shall

be in accordance with AFSCM 375-1, and shall be subject to approval of the Titan X SLV Project Office.

3.2 Critical Design Review

The contractor shall conduct a critical design review 180 days after award of contract. This review shall be in accordance with AFSCM 375-1, and shall be subject to approval of the Titan X SLV Project Office.

3.3 Final Acceptance

Final acceptance of the contractor's work shall be indicated by accomplishment of a DD Form 250 reflecting technical acceptance of the designs provided by the contractor and completion of all contractual requirements as specified in this SOW and associated documents. In the event there are exceptions to acceptance reflected on the DD Form 250 or attachments thereto, the contractor shall be required to correct all exceptions as specified within the time limit mutually agreed upon during the execution of the DD Form 250.

4.0 PERFORMANCE REQUIREMENTS

4.1 Components

The PTPS and its component parts may incorporate those technological advancements which can be utilized without unnecessary development risks or expense inappropriate to performance gain. PTPS equipment and components fall into four categories: liquid, vent, nitrogen and electrical.

Electrical components will be designed to operate from 28 VDC. Components are to be either hermetically sealed or continuously pressurized with nitrogen gas to a minimum of 50 inches of water pressure to prevent contamination.

Liquid components, defined as those items normally in direct contact with propellants, shall be designed to withstand an operating pressure of 225 PSIG, proof pressure of 350 PSIG, burst pressure of 900 PSIG. All liquid components are to be designed to have a self-draining capability or are to be provided with drains. [Further equipment details follow.]

The system shall have the capability of transferring fuel from the RSV to SLV tanks at a rate of 50 GPM to 200 GPM. Tanking of the two SLV stages shall be performed sequentially.

4.2 Time Requirements

The system is to be so designed that fuel and ozidizer can be loaded into the SLV tanks within a 90 minute period, once the requirement to transfer propellants has been given. Maximum time requirements for the individual transfer functions are given below (only for fueling, since oxidizer functions are considered to be identical):

(a) Transfer fuel from RR car to RSV - 4 hours

(b) Transfer fuel from RSV to SLV - 90 minutes

All times are for maximum propellant loads.

5.0 ENVIRONMENTAL REQUIREMENTS

5.1 Climatic

The PTPS shall be designed to operate under the following conditions:

(1) Ambient temperature

(a) Operating - 32F - 90F

(b) Non-operating - 20F to 115F

(2) Humidity

The equipment shall be operable during and after subjection to ambient humidity of 95%.

(3) Barometric pressure

(a) Operating and non-operating - sea level to approximately 10,000 feet

The PTPS shall incorporate provisions designed to protect against salt, sand, and dust in accordance with the requirements of MIL STD 210A. Wind, iceload, rainfall, fungi, provisions are not applicable.

5.2 Mechanical

The PTPS shall be designed to meet the following mechanical conditions:

(1) Vibration -- 50-100 cycles for 15 seconds

(2) Shock -- minimum 10g over burst pressure

6.0 SERVICE LIFE

The design and installation of the PTPS shall be such that a minimum operational life of 10 years with required maintenance will be achieved.

7.0 PERSONNEL SUBSYSTEM

7.1 Manpower Requirements

[The following was created for and presented to the high skill, low number group (I) only.]

The contractor shall design and develop the PTPS for operation and maintenance by Air Force personnel. It is desirable that only a minimum number of personnel be required to man the system. This criterion shall have top priority in any design situation in which skill level and number of personnel must be traded off. It is anticipated that operational personnel will be a small number of highly trained specialists who possess considerable skill in the performance of their duties. It is anticipated that not more than 15 personnel will be available to operate and maintain the system. Seventy-five percent of these personnel will be 5 and 7 level Air Force personnel; the remaining 25% will be 3 level Air Force personnel. In view of the hazardous nature of the system, however, situations in which human error could occur are to be avoided. For this reason the PTPS shall be designed to applicable sections of MIL STD 803A-1.

[The following was created for and presented to the low skill, high number of personnel group (II) only.]

The contractor shall design and develop the PTPS for operation and maintenance by Air Force personnel. A primary goal in design of the PTPS is that these personnel shall require a minimum amount of training or skill in the performance of their duties. Every effort shall be made to avoid the necessity for complex manual operations. It is anticipated that not more than 20 personnel will be available to operate and maintain the system. Seventy-five percent will be 3 level Air Force personnel; the remaining 25% will be 5 and 7 level Air Force personnel. In view of the hazardous nature of the system, situations in which human error could occur are to be avoided. For this reason, the PTPS shall be designed to applicable sections of MIL STD 803A-1. In any design situation in which skill level and number of personnel must be traded off, the requirement for minimum skill level shall be accorded first priority.

The following is a definition of the Air Force skill levels referenced in this statement of work.

3 level -- Performs simple manual operations readily (without assistance) but may require assistance (supervision or use of manuals) with more complex operations, particularly those involving a combination of tasks or requiring significant decisions involving extrapolation of data or judgment. Performs simple responses quickly, shows hesitation or significant delay with more complex ones. Has a low error probability (1-5%) for simple or moderately precise operations, which rises to an extremely high level for complex operations (50%).

5 level -- Performs simple tasks and those requiring moderate precision with little difficulty but may require assistance (supervision or use of a check-list) with more complex operations, particularly those involving significant decisions or judgments requiring extrapolation of data. Performs moderately precise responses quickly and with assurance, but shows hesitation or delay with more complex ones. Has a very low error probability for simple or moderately complex operations (1-2%) which rises to a significant error rate for highly complex operations (20%).

7 level -- Displays little difficulty in performing all operations required including those of a nature involving judgment and extrapolation of data. Little or no supervision required. Responses are quick and assured, requiring no assistance from others or from manuals/checklists. Has extremely low error probability for simple and moderately complex operations (.1%) which rises to approximately 5% for highly complex ones.

The 4 level requires administrative skills which are not significant for PTPS operations.

7.2 Information Provided

The contractor will develop and maintain analytical data in the form of task and equipment information which will define the interrelationship of functions to be performed by systems, people and hardware. This material will not duplicate other analytical efforts. The information will contain a description of personnel tasks and skills required to operate, maintain and control the PTPS. The contractor shall provide to his Engineering Department the following inputs:

(1) Personnel/equipment task analysis;

(2) Human engineering analyses;

(3) Quantitative and Qualitative Personnel Requirements Information (QQPRI);

(4) Training Requirements Analyses.

7.3 Human Engineering

As outlined in MIL-H-27894A, the contractor will apply human engineering to hardware and system design to assure optimum operation and maintenance, utilization of the human as a component in the system, and reduction of tasks affected by human limitations to a minimum. This will include human design considerations for maintenance, operations, communications, illumination, noise level, reliability, safety, climate and environment. Studies and recommendations will be directed by Titan X SLV Project Office for the improvement of procedures and design as inefficient operation situations are detected.

8.0 SAFETY

Safety engineering will be a prime consideration in the design of the PTPS. Personnel safety requirements shall be in accordance with AFTO 11C-1-6. All designs shall incorporate maximum protection for operating and maintenance personnel against hazardous conditions. Adequate provisions shall be made to warn and/or protect personnel and equipment against injury and damage. All designs shall be reviewed by qualified safety engineers.

9.0 RELIABILITY

9.1 Requirements

The availability of the PTPS, defined in terms of being able to initiate propellant transfer when required, shall be .9998. The reliability of the PTPS, defined in terms of its being able to complete propellant transfer within previously stated time requirements, given that transfer can be initiated, shall be not less than .9950.

9.2 Prediction

An initial prediction of reliability performance shall be submitted to the procuring activity no later than 60 days after award of contract. A revised reliability prediction shall be issued no later than every 90 days from the submission of the initial report. A comparison of the predicted MTBF with the required MTBF shall be made. A separate prediction for the reliability of human performance shall also be made. When the predicted figure is less than the requirement, the contractor shall accomplish such changes in design, part application and part stress and personnel task allocation as are necessary to raise the predicted MTBF to the required value.

10.0 MAINTAINABILITY

The contractor shall establish a maintainability program in accordance with applicable sections of MIL-M-26512 and Appendix A thereto. The terms and definitions for maintainability not otherwise described or delineated shall be in accordance with MIL-STD-778.

As a design goal the PTPS shall incorporate factors that enhance its maintainability and accessability. The maintainability characteristics shall be such as to minimize the requirements for special tools or support equipment, inspection, servicing, test, replacement and overhaul operations required to restore operational capability with a minimum expenditure of time, men and materials. When other factors prohibit compliance with this requirement, special tools and service equipment shall be identified. The inclusion of maintainability characteristics as an inherent feature shall occur simultaneously with initial design and shall be continually analyzed and controlled throughout the development cycle. The equipment shall be designed so that the following system mean and maximum corrective maintenance times shall not be exceeded:

Mean Corrective Maintenance Time (M_{ct}), 6.0 hours

Maximum Corrective Maintenance Time (M_{max}), 19.0 hours

SESSION 1

Instructions To Participating Engineers

The information presently available to you consists of the Statement of Work (SOW), which includes Figures 2 and 3 (the top level function flows for fueling) and the list of personnel functions (including Figures 4 and 5) which represent an analysis, based on the SOW, of the personnel functions that must be performed to accomplish PTPS requirements. [In this and subsequent instructions underlined material was provided only to experimental subjects.]

Based on this information, we want you to describe, in as much detail as possible, all the functions and subfunctions which must be performed to accomplish:

1. Transfer of fuel from the railroad car to the storage tanks;

2. Storage of fuel;

3. Transfer of fuel from the storage tanks to the rocket tanks.

We would like this in the form of two flow diagrams indicating the sequential or parallel relationships among subfunctions. One flow diagram would be for transfer of fuel to the RSV including storage; the other would be for transfer of fuel from the RSV to the rocket tanks. On each flow diagram you will indicate which functions are to be performed primarily by equipment and which primarily by personnel. Do this by putting an X beside each personnel function.

Before you begin this task, however, but after you review the SOW and the flow diagrams, there are a number of questions I would like you to answer. I will record your answers on this tape recorder.

1. Do you have enough information about system functions and equipment requirements to accomplish your task?

2. Do you have enough information about personnel functions involved in the PTPS?

3. What additional information would you wish to have about either system or equipment functions or personnel functions?

4. What information would you ordinarily receive at this stage of system development?

Figure 4
Personnel Functions - Transfer Fuel To RSV

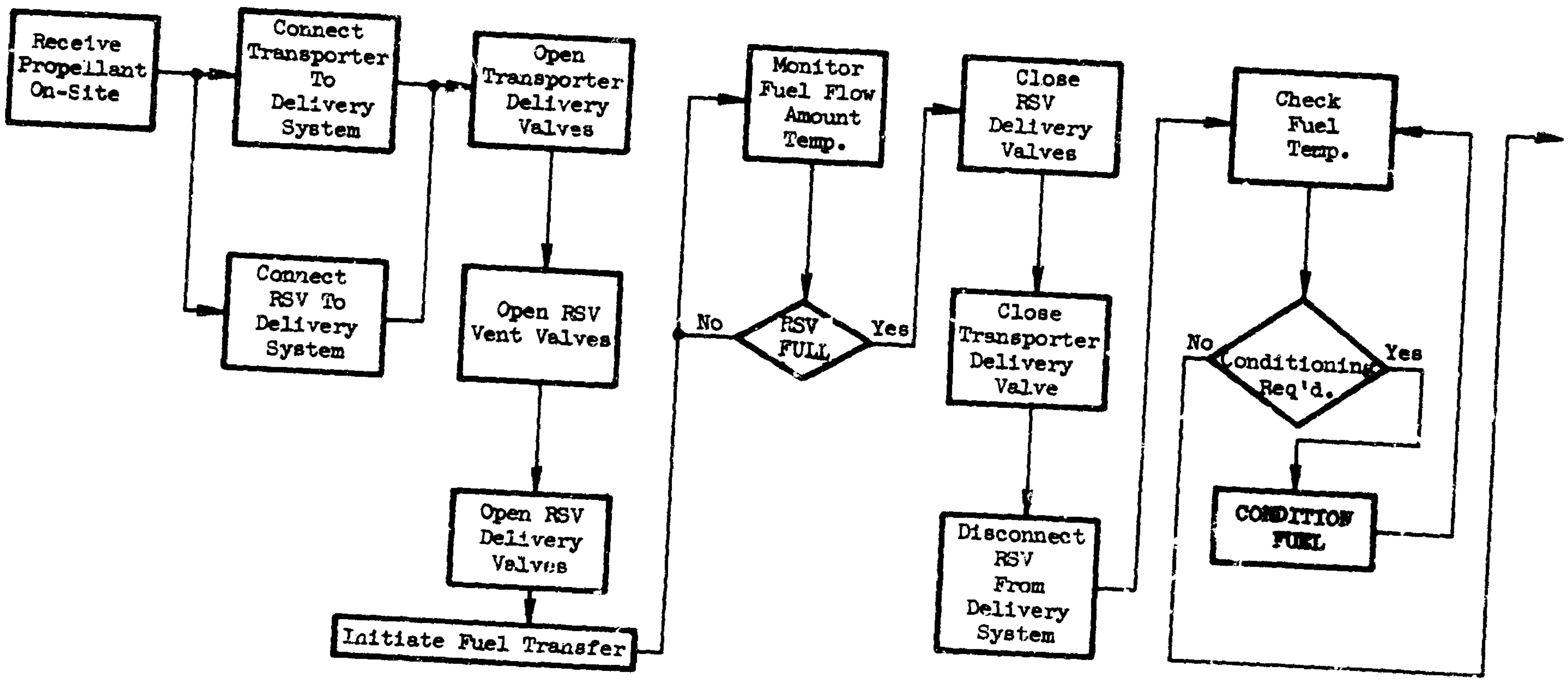
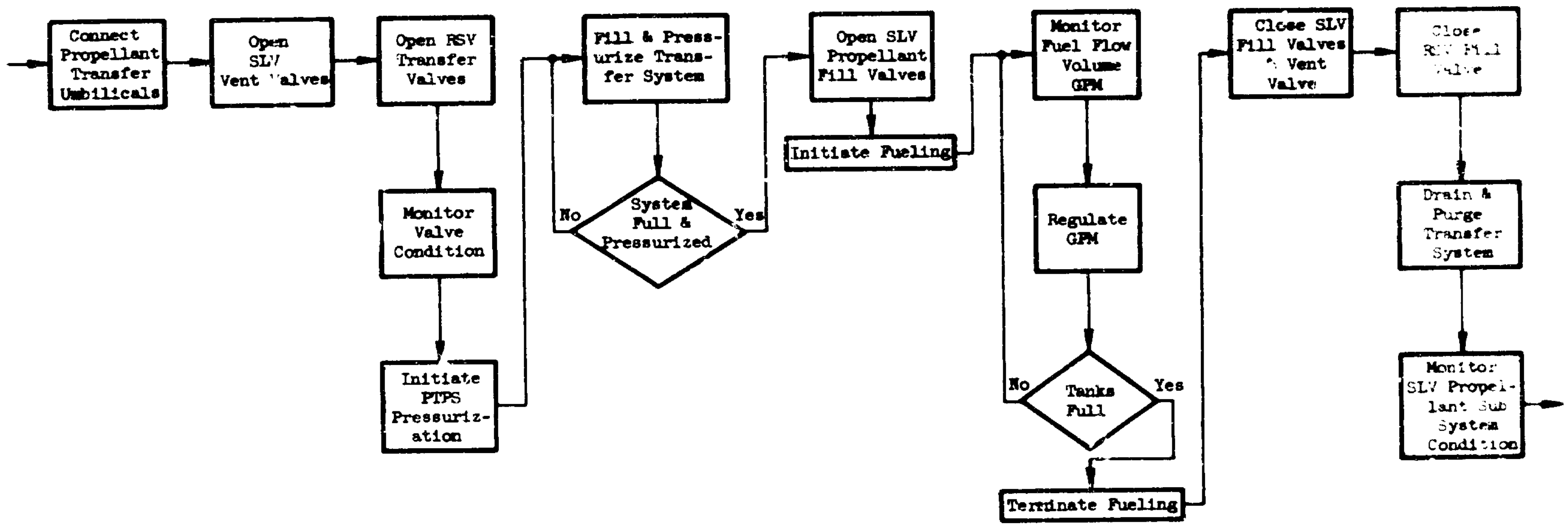


Figure 5
Personnel Functions - Transfer Fuel to SLV



5. How do you think the personnel requirements in the SOW will affect your design? Do you think they will have any significant effect on your design? In what way?

The following is for experimental subjects only: [Control subjects did not see this section of the instructions.]

6. Do you find the flow diagrams of personnel functions (Figures 3A and 4A)useful?

7. Would you ordinarily expect to receive information about personnel functions at this stage of system design?

8. Do you think this information is too early, too late, or just in time?

9. Could you have derived the personnel information in the flow diagrams on your own? Would you ordinarily have done so?

10. Do you have any difficulties understanding the personnel input?

11. Do you feel there is enough information about PTPS requirements in the SOW to develop these personnel functions?

12. Which version of the personnel functions do you find more useful, the list or the flow diagrams? Is there any real difference between them?

13. Can you apply the personnel input to your design task?

14. What design implications can you draw from the personnel inputs?

The engineer will then proceed to develop the two flow diagrams. At the conclusion of the session he is told (both experimental and control subjects): Now that you have completed your task, I would like to review your diagrams with you. Specifically, I want to know why you included the particular functions you did, and whether any information you received at the start of the session suggested the functions you listed. I also want to know why you allocated certain functions to equipment and others to personnel.

At the conclusion of the session, the experimenter will retrieve the diagrams the engineer has developed and give him the next session's inputs. A xerox copy of his diagrams will be made, and they will be returned to him on the same day.

Transfer Fuel from RR car to RSV

1. Find and connect the appropriate flex hoses from the RR car to the storage tank.

2. Open fill valve on RR car and storage tank.

3. Open vent valves on storage tank.

4. Initiate fuel transfer.

5. Monitor amount of fuel being transferred.

6. Close storage tank and RR car fill valves.

7. Disconnect flex hoses from storage tank.

8. Monitor fuel temperature.

9. Adjust fuel temperature.

Transfer Fuel from RSV to SLV Tanks

1. Connect PTPS umbilicals to missile tanks.

2. Open rocket tank fill and vent valves.

3. Open storage tank fill and vent valves.

4. Determine that fill and vent valves are open, drain valves closed.

5. Initiate pressurization of PTPS.

6. Signal return of all personnel from the launch area.

7. Initiate filling of PTPS.

8. Determine that fuel has begun to flow.

9. Monitor fuel flow and amount.

10. Regulate amount of fuel being transferred.

11. Check fuel temperature and adjust.

12. Determine that rocket tanks are filled to the proper amount.

13. Stop transfer of fuel.

14. Close storage tank fill valves.

15. Drain and close PTPS fill lines.

16. Close rocket tank fill and vent valves.

SESSION 2

Instructions To Participating Engineers

In this session, we ask you to imagine that a period of time in the development of the PTPS has elapsed and that consequently additional information, gathered by other members of the project team, is available concerning PTPS functions. This information is presented in two forms, a partially completed Requirements Allocation Sheet (RAS) and a more detailed functional flow diagram of personnel operations (Figures 6 and 7). On the RAS the following is available:

1. Major subfunctions (Function Name and No. Column);

2. Initial design requirements for these subfunctions (Design Requirements Column);

3. Personnel tasks which must be performed to accomplish these subfunctions (Tasks Column);

4. Performance requirements to accomplish these personnel tasks (Performance Requirements Column).

The flow diagram of personnel operations corresponds to the tasks listed on the RAS.

Your job in this session is to take the initial design requirements together with the other information available to you (including information from the preceding session) and describe the characteristics of the equipment needed to accomplish the design requirements. We would like you to describe in as much detail as possible the following:

1. The nature of the components required (e.g., motors, valving, piping, pumps, etc.)

2. How this equipment would operate to perform its functions

3. Function limitations and tolerances

4. How the equipment ties in with other equipments and functions

5. The physical facilities (e.g., geographic layout) you would need to have to implement the design requirements.

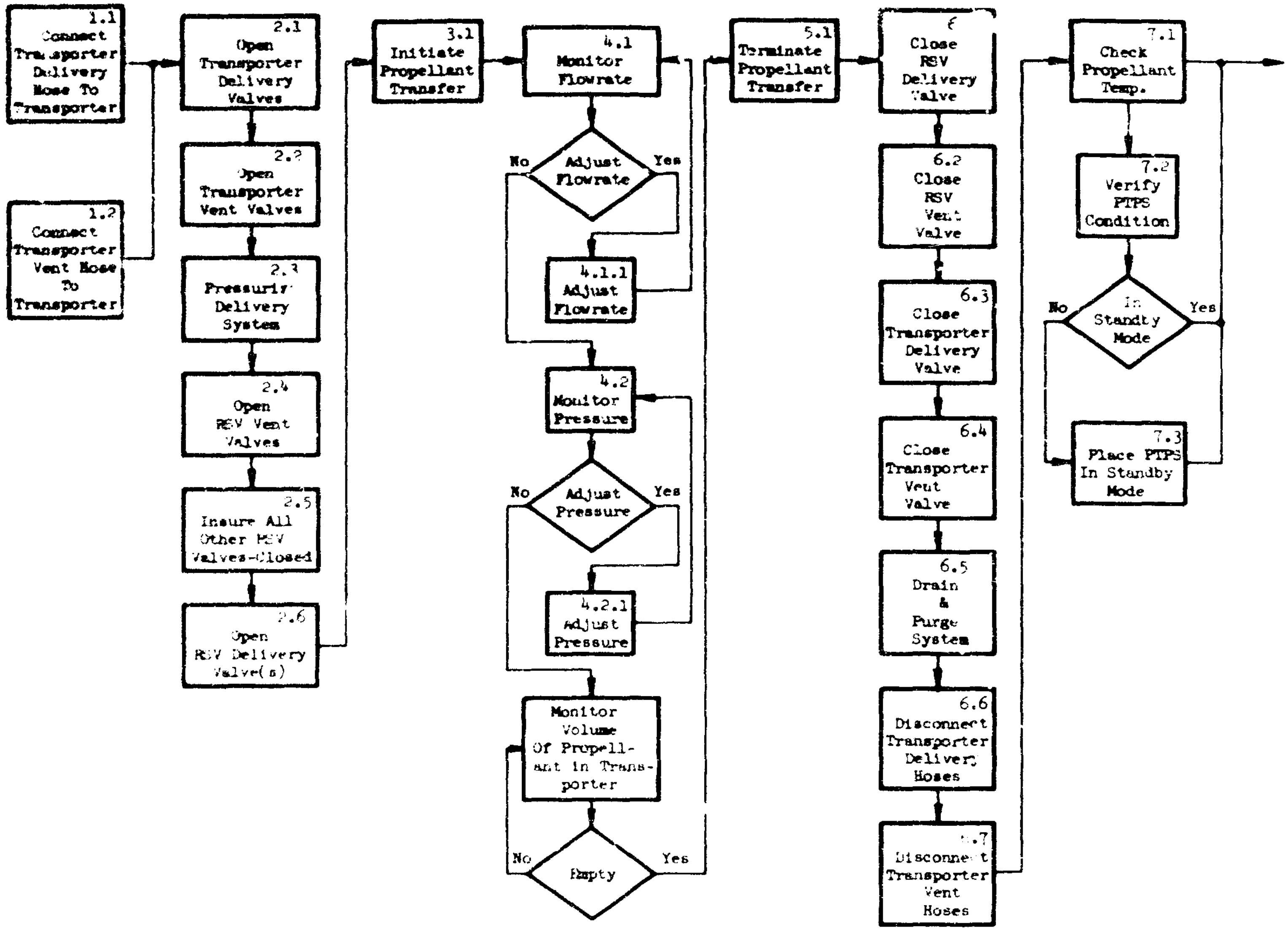
Indicate only general dimensions, without worrying about precise tolerances.

Figure 6 - Sample Requirements Allocation Sheet (Operations)

Requirements Allocation Sheet	Subsystem: Propellant Transfer System; Functional Flow Dwg No.: Fuel		End Item Identification		Personnel & Training Equipment Reqmt				Tech Manual Reqmt
Function Name & No.	Design Reqmt	Facility Design Reqmt	Nomenclature	Design Form or ... 2 No.	Tasks	Time Reqd (hr)	Perform. Reqmt	Eng & Eng Equip. Reqd	
1.0 Connect Transporter delivery hose.	A requirement exists to transfer fuel from a transport vehicle to the storage tank				1.1 Connect Transporter delivery hose to fill valve on fuel transporter		Find, lift hose, move to transporter. Secure hose coupling to transporter fill valve.		
					1.2 Connect Transporter vent hose to vent valve on Transporter.		As above, to transporter vent valve.		
2.0 Pressurize and Prime System	A requirement exists to pressurize and prime the transporter delivery system before transferring fuel.				2.1 Open Transporter delivery valve(s)				
					2.2 Open Transporter vent valve(s)				
					2.3 Pressurize and prime system		Allow fuel to flow into lines in order to prime system. Controls required to pressurize system. Consider possibility of any feedback concerning whether pressurization has been achieved, amount of pressure achieved, and necessity for regulating pressure during transfer. Consider whether this should be accomplished manually or automatically.		
					2.4 Open RSV vent valve(s)		Access to vent valve. Consider identification of valve.		
					2.4.1 Insure all other RSV valves are closed.		Since indication of valve positions is required, consider possibility of display of valve position. Alternative is manual inspection of valves.		
					2.5 Open RSV delivery valve(s).		Access to delivery valve.		
3.0 Initiate Propellant transfer					3.1 Start fuel flow.		Control required to initiate fuel flow.		

Control No. ______ Revision ______ Date ______ Approval ______ Document No. ______ Page No. 1

Figure 7
Personnel Operations Flow Diagram



Before you go ahead, however, but after you review this material, I would like to ask a few questions:

1. Do you have enough information to describe the equipment you need to accomplish these functions?

2. If not, what is lacking? What information would you like to have? What information would you expect to have?

3. Is there too much informat. for this stage of system development?

4. What information about personnel functions and tasks would you wish to have to perform your task in this session?

5. What personnel information would you ordinarily have at this stage of system development? Is this information sufficient?

6. If the number of men needed to operate and maintain the PTPS and their skill levels were available now, would it help you in describing the required equipment? If so, how?

The following questions are asked only of the experimental subjects:

1. Do you find the information on personnel tasks and performance requirements on your RAS sheet useful in performing today's task?

2. Would you ordinarily expect to receive information of this sort at this stage of system design? Would you generate this information yourself? Is this information too early, too late or just in time?

3. Do you understand the personnel information? If not, what do you not understand?

4. Is the performance requirements information on the RAS more, or less or equally useful as the information under the task column?

5. Which version of the personnel task information do you find more useful, the flow diagram or the RAS material?

6. Can you apply the personnel information to your analysis of equipment requirements?

7. What equipment design implications can you draw from the personnel information?

[Procedures for debriefing at the conclusion of the session are the same as in Session 1.]

SESSION 3

Instructions To Participating Engineers

In this session additional information is available to you concerning the primary functions which the PTPS must perform.

The information consists of more detailed design requirements and equipment characteristics than was available previously. In addition, an analysis has been made by the Human Factors section of the control/display equipment which the PTPS system will require. [Not given to control subjects.] Naturally you may use all your previous information.

What we want you to do in this session is to review and amplify your previous equipment descriptions in the light of the new information. In addition we would like you to develop a set of equipment flow diagrams which describe in as much detail as you can how the equipment operates.

Before you go ahead, however, I should like to ask a few questions with reference to the new information provided in this session:

1. Do the new inputs provide you with enough information to describe the equipment you need in as much detail as you would wish?

2. What additional information would you like to have? Of what type? What additional information would you expect to receive?

3. What information about personnel activities would you wish to have to make up your equipment flow diagram?

4. What personnel information would you ordinarily have at this stage of system development? Is this information sufficient?

5. If the number of men needed to operate and maintain the PTPS and their skill levels were available now, would it help you in developing the equipment flow diagrams? If so, how?

The following questions are asked only of the experimental group:

6. Do you find the memorandum on control/display requirements useful in performing today's task?

7. Would you ordinarily expect to receive information of this sort at this stage of system design? Would you generate this information yourself? Is this information too early, too late, or just in time?

8. Is the information sufficiently precise and detailed; too general?

9. Can you apply this information to your analysis of equipment requirements?

10. What equipment design implications can you draw from the memorandum?

11. Do you agree or disagree with the recommendations made in the memorandum?

As in previous sessions, a review of the engineer's design outputs will be performed at the close of the session.

Supplementary Information To Be Added To
Requirements Allocation Sheets After Approval

Function: Transfer Liquid Propellants to Ready Storage Area

A requirement exists to transfer Titan X SLV liquid propellants from the Propellant Tank Car Storage Area or a Bulk Storage Area to ready storage areas at Launch Complex 40.

The Titan X SLV liquid propellants are:

A. Hydrazine/unsymmetrical-Dimethylhydrazine (50% N_2H_4 - 50% UDMH), which hereafter will be referred to as fuel. Reference is made to MIL-P-27402 (USAF), 25 August 1961.

B. Nitrogen Tetroxide (N_2O_4), which hereafter will be referred to as oxidizer. Reference is made to MIL-P-26539A, 31 July 1961.

The maximum amount of fuel required in the fuel holding area at any one time is 22,000 gallons. The maximum amount of oxidizer required in the oxidizer holding area at any one time is 28,000 gallons.

The fuel and oxidizer must be transported to separate ready storage areas by either railroad tank cars or road tank trailers.

A. Railroad tank cars will be the primary mode of transportation.

The fuel holding area must be separated from the oxidizer holding area by a minimum of 700 feet.

It is anticipated that fuel will be delivered in railroad tank cars similar to Model ICC 103C-W which has an approximate capacity of 7,500 gallons.

B. Provisions must be made to obtain personnel access to the dome housing on each railroad tank car.

Platforms, ladders and handrails must be provided to gain access to the dome housing on each railroad tank car. Walkways for each tank car must be constructed so that they can be moved out of the way for tank car movements.

The hazards (toxic, fire, corrosive) presented by each of the propellants require preparatory tasks and functions. These must be accomplished prior to the time either of the two propellants are, by any means, removed from a tank car. It is required to validate all

supporting tasks and functions necessary to the actual transfer of propellants as follows:

A. Safety regulations and procedures for the handling of liquid propellants shall be provided and strictly enforced in accordance with the following document and applicable waivers:

   1. AFTO 11C-1-6 General Safety Precautions for Missile Liquid Propellants, dated 27 November 1961, latest revision.

B. Criteria for the protection of personnel have been established for all functions performed during transfer of propellants.

   1. Complete protective clothing and the conditions under which it will be used.

   2. Partial protective clothing and the conditions under which it will be used.

   3. Portable toxic vapor detectors which are used to sense the quantity of UDMH and NO_2 vapor in the atmosphere.

C. In order to accomplish the propellant transfer operations, the following communication systems must be provided:

   1. Dial telephone

   2. Public address

   3. MITOC (Missile Technical Operations Communication)

D. A hazard warning system must be provided to alert personnel to the presence of propellants on the launch complex.

The existing requirement to transfer propellants to ready storage vessels must be accomplished by utilizing a portion of the propellant (fuel and oxidizer) transfer system.

That portion of the PTPS that will be used for transfer consists of fluid equipment end items, components, instruments, and connecting piping that together enable propellants to be received from delivery vehicles and stored.

The requirements for the portion of the propellant transfer system to be utilized for this function are as follows:

A. The equipment end items (ready storage vessel(s) and propellant loading units), fixed piping and components all of which are located in the holding areas will be utilized.

B. A requirement exists for a central control, and distribution unit for the transfer operation.

C. The central control area should contain centrifugal pumps, totalizing flowmeters in series, an automatic flow control system, associated valves, monitors, and controls necessary to perform the transfer function.

1. Propellant shall be pumped from the delivery vehicle into the storage vessel(s) where it is stored, bypassing the flow measurement subsystem if desired. Pump shall operate up to a maximum flow rate of 200 GPM.

   A nominal transfer rate of 100 GPM is selected as time is not a prime consideration during this period and increased reliability of equipment should result.

2. Provide pressurization of the delivery vehicles to satisfy the pump NPSH requirements. The NPSH requirements shall be based on the propellants being pumped between plus 45°F and plus 90°F. The delivery vehicles shall be so positioned that propellant can be pressure transferred to the PLU (Propellant Loading Unit). In order to prime the pump (PLU) the approximate GN_2 pressure to the delivery vehicle shall be as follows:

(1)	Fuel:	20 psig to trailers
		30 psig to tank cars
(2)	Oxidizer:	40 psig to trailers
		50 psig to tank cars

D. The purge and vent subsystem within the PLU that will be used shall consist of control valves, piping, and back pressure regulators that enable "closed or open loop" transfer. The same piping arrangement shall also provide the capability of blanketing and purging the transfer system.

E. The nitrogen subsystem within the PLU that will be used shall consist of pressure regulating valves, control valves, instrumentation, and associated piping to meet the transfer requirements. The subsystem shall reduce nitrogen gas supply from 150 psig to pressures required for the following uses at supply flows up to 0.5 lb./sec:

1. Blanket pressures for fuels:

   7.2 to 12 psig

   for oxidizer:

   7.2 to 23 psig

2. Pressurization: 20 to 50 psig

3. Purge: 20 to 30 psig

[3½ single-spaced pages of equipment information were also provided.]

Control-Display Recommendations

To: Project Engineer, PTPS Project

From: Human Factors Section, Personnel Subsystem Group

Subj.: Control-Display Recommendations resulting from Human Factors Analysis

The following represents our analysis of control-display requirements based on the limited amount of information available to date.

1. Open and closed indications should be provided for all fill and drain valves in piping leading to Stage I and II missile propellant tanks, as well as for their respective vent valves. The same recommendation can be made for the bleed valves for both Stage I and II fill lines. Since these valves may have to be operated remotely, (once propellant is in the lines), the use of illuminated (for display) pushbuttons should be considered. Valves which are never operated remotely should not be displayed. The indications provided should display the actual position of the valve, not merely the fact that electrical energy has been supplied to the line leading to the valve (which has often been the case).

One of the problems involved in displaying valve positions is that in different operating sequences certain valves should be open while others are closed. It would therefore be necessary not only to indicate the actual position of the valve but also the position the valve should be in for that sequence. Consideration should also be given to arranging the valve displays in a schematic of the PTPS system. This might assist personnel in understanding the functional interrelationships of the valves.

2. Pressure indications should also be provided for Stage I and II missile tanks, as well as controls for pressurizing these tanks.

3. Controls should be provided to turn the unit supplying the nitrogen gas under pressure on and off. Pressure indications will also be needed for the RSV as well as for the fuel transport vehicle.

4. Controls for initiating and stopping fuel flow are required; also to control blanket pressure within the PTPS lines. A meter is required for displaying the flow of fuel. Digital counters should be made available for determining the amount of fuel actually being tanked. This will involve a linkage with sensors located in the missile propellant tanks.

5. The temperature of the fuel at each place in which it is sensed should be displayed. Consideration should be given to whether all locations should be recorded simultaneously, or successively, and whether the precise temperature should be indicated or simply an indication of over or under temperature.

6. All hoses requiring manual connection should be color coded or otherwise marked to make their identification easy or their connections (pins) so coded as to make cross or incorrect connection of hoses impossible.

7. Consideration should be given to the centralization of all the control/display functions listed above within a single station or console. If such a central station were established, consideration should also be given to providing a means of automatically checking out the PTPS from that station. Such a checkout facility might include the capability of isolating PTPS malfunctions to individual valve or other major components.

Should a central control station be established, consideration should also be given to having redundant and parallel controls and displays for each of the various operational/maintenance sequences. Thus, the station might consist of a section for transferring fuel from the transporter to the RSV, a section for fuel transfer to the SLV, and one for maintenance/malfunction identification. Similar sections for the oxidizer side of the PTPS would also be required. Certain controls and displays required for transferring fuel from the transporter to the RSV may have to be included on the transporter itself. Under those circumstances it would be necessary to devise some means of integrating centralized control functions with those of the transporter.

8. Your comments with regard to the recommendations made in this memorandum would be greatly appreciated.

SESSION 4

Instructions For Participating Engineers

Information supplementing what you have been given previously concerning the equipment characteristics of the PTPS has become available. In addition, the Personnel Subsystem Group has provided a preliminary task analysis of PTPS operations. [Control subjects do not receive the task analysis.]

In this session we will ask you to review both of these inputs and, keeping in mind also the information you have received previously, we want you to develop a list of the control-display hardware required to operate the PTPS. Your list should describe the following parameters:

1. Nature of the control or display (e.g., gage, indicator, lever, etc.);

2. Any alternative control or display you can think of;

3. The function to be performed by the device;

4. Any characteristic of the device that you can think of;

5. Where the control or display should be located;

6. The reason for the control or display.

In reviewing the material available to you, we should also like you to think a little about the number and type of men you would need to operate and maintain the PTPS. By type of men we mean their training, experience and skill level. We will ask you about this at the conclusion of the session.

Before you go ahead to make up your list, however, I would like to ask a few questions:

1. Do you now have enough information to list the control-display hardware you would need to accomplish PTPS functions? Subsequent questions are essentially the same as in previous sessions.

The following questions are asked only of experimental subjects:

1. Do you find the preliminary task analysis from the Personnel Subsystem Group useful in performing today's task?

2. Would you ordinarily expect to receive information of this sort and to this level of detail at this stage of system development? Would you generate this information yourself?

3. Do you have any difficulty in understanding the task analysis? If so, what aspect of it gives you difficulty?

Take up each part of the task analysis separately and ask about the engineer's understanding of that part.

4. Does the time information have any design implications for you? Does it help with the list of control-display hardware?

5. Does the performance requirements information have any design implications for you? Does it help with the list of control-display hardware?

6. How about the performance probability figures? Can you interpret them in terms of the design of the PTPS?

7. How about the difficulty index?

8. How well do you feel you know what the PTPS personnel should do in operating the system? Have any of the personnel inputs to date helped to give you a better understanding of these operations?

9. As between a task which is simple and one which is complex, what design differences would you incorporate? What would you do to make the complex task simpler?

Additional Supplementary Information

Prover Loop

Due to the importance of an accurate SLV propellant load, the flowmeter circuit should be verified before the missile is loaded. This verification circuit will include a calibrated prover tank of 100 gallons and two level sensing devices, one installed at the bottom and one installed at the top of the prover tank. Propellant flow is directed into the tank from the bottom. When liquid contacts the bottom liquid sensor, the flow totalizer stops. he flow measuring system is verified by comparing the totalizer number with the known volume of the prover tank.

The prover tank will be calibrated to 100 gallons $\pm$ .05% by volume. A full length sight glass should show liquid level just above the top sensor and indicate the empty condition after drainage.

Flow Control Value

A flow control valve (FCV-1) will control propellant flow rates within the transfer system. It is normally closed and moves to the full open position with the application of supply pressure (60 PSI) and a 15 PSI instrument N_2 signal. The supply pressure is controlled by a 3-way solenoid valve. The instrument N_2 signal is supplied by the recorder controller. The position of the valve is proportional to the 3-15 PSI instrument signal.

Check Valve FL-FPLU-CHV-1

Downstream of the FCV a check valve will be provided. This component is placed here to prevent back flow through the system. It is a swing type check valve which opens with 1.9 PSI or less. It is made of stainless steel with seals of virgin unplasticized teflon.

Quick Disconnects

The quick disconnect coupling(s) will consist of an airborne half and a ground half. The coupling is used during the filling of the vehicle propellant tanks from the ground propellant supply, draining vehicle tanks into the ground system, venting nitrogen gas and propellant vapors from the vehicle tanks into the vent system, etc.

[In all, 7 single-spaced pages of supplementary equipment details were provided]

Preliminary Task Analysis

To: Project Engineer, PTPS Project _______________, 1967

From: Personnel Subsystem Group

Subj: Preliminary Task Analysis of PTPS Operations

The following is an initial analysis of PTPS operations in terms of the personnel performance requirements (including task complexity and safety provisions), the estimated length of time required for the operation and the probability that the operation will be performed correctly. A difficulty index is also provided.

The following should be noted. A blank in the time column indicates that the time will be variable, depending on individual operational conditions.

The performance probability indicates the percentage probability that, if the task were repeated over 10,000 operating cycles, the task would be performed correctly. For example, if the probability is .9995, this would mean that one would expect the operator to make an error only 5 times out of 10,000. In skill equivalents, these probability values mean the following:

.9900 - .9999 = extremely simple task requiring little skill.

.9800 - .9889 = moderately precise task requiring some training and a fair degree of experience.

.9500 - .9779 = highly precise task requiring judgment, a good deal of training and extensive experience.

Difficulty Index

1. Level 1 involves simple manual operations like throwing a switch or pushing a button; or simple recognition of go-no go indications. The operation may be performed by a skilled operator without a checklist or by a novice with a checklist. Only simple judgment would be required. The information needed to perform the operation would be limited to direct recall of simple facts involved in recognition of devices and their general function. Extremely low human error potential: for experienced personnel, .001%; for inexperienced personnel (although trained), .01%.

2. Level 2 involves moderately precise manual operations such as adjusting a potentiometer or torqueing a wrench to a predetermined value. From a visual standpoint it might involve reading a quantitative meter or interpolating a scale value. The operation might involve the coordination of a manual action with a visual one, whereas level 1 would not. A moderate degree of judgment would be required, such as that involved in estimating how long an action should be performed, performing a visual check, or making decisions based on information from several sources. The information needed to perform the operation might involve the principles of system operation, e.g., knowing the effects of activating a control on downstream valves. There is moderate error probability for experienced personnel, .01%; for inexperienced personnel, 5%.

3. Level 3 involves very precise, complex manual operations such as those involved in removing or replacing delicate components. It may involve a high degree of perceptual precision, such as reading frequency waves or discriminating slight differences in shades of the same color (e.g., determining corrosion). A considerable amount of decision-making judgment is required as in troubleshooting a failed device or in coordinating the actions of a number of personnel in the same system operation. The information needed to perform the operation would involve the organization of many highly detailed facts derived from memory and deduction of their implications for action. There is an extremely high human error potential for inexperienced personnel, e.g., 50-75%. For experienced personnel the error probability is about 10-20%.

PERSONNEL TASKS	TIME	PERFORMANCE REQUIREMENTS	PERFORMANCE PROBABILITY	DIFFICULTY INDEX
1.1 Connect Trailer delivery hose	5	Simple manual task, but requires protective clothing be worn (unless otherwise noted all operations of the FTPS require personnel wear protective clothing as protection against fuel vapor).	.9975	1
1.2 Connect Trailer vent hose	5	Simple manual task.	.9975	1
2.1 Open Trailer delivery valve	2	Simple manual tasks performed on command of fueling supervisor (communications link required) and reported to him upon completion.	.9961	1
2.2 Open Trailer vent valve			.9961	1
2.3 Pressurize and prime system	-	Simple task with possible hazard existing in the high gas pressures in the lines. Communication link to fuel supervisor is required.	.9958	1
2.4 Open RSV vent valve	2	Simple manual task requiring communications link and awareness of high pressure danger.	.9961	1
2.5 Insure all other RSV valves are closed	5	Simple task requiring communication link to fuel supervisor.	.9953	1
2.6 Open RSV delivery valve	2	Simple manual task requiring communication link.	.9961	1
3.1 Initiate fuel flow	2	Simple task requiring communication link.	.9978	1
4.1 Monitor fuel flow rate	30	Moderately precise tasks requiring training and hand-eye coordination; also requires a communication link to the fueling supervisor.	.9848	2
4.2 Monitor fuel pressure	30		.9848	2
4.3 Monitor volume	30		.9848	2

PERSONNEL TASKS	TIME	PERFORMANCE REQUIREMENTS	PERFORMANCE PROBABILITY	DIFFICULTY INDEX
5.1 Terminate fuel flow	2	Simple task performed upon command.	.9995	1
6.1 Close RSV delivery valve	2	Simple manual task requiring task 2.6 be performed in reverse order.	.9976	1
6.2 Close RSV vent valve	2	Simple manual task requiring task 2.4 be performed in reverse order.	.9976	1
6.3 Close trailer delivery valve	2	Simple manual task requiring task 2.1 be performed in reverse order.	.9976	1
6.4 Close trailer vent valve	2	Simple manual task requiring task 2.2 be performed in reverse order.	.9976	1
6.5 Drain & purge system	30	Simple task requiring communication between fuel hardstand, supervisor, and waste tank operators.	.9976	1
6.6 Disconnect trailer delivery hose	5	Simple manual tasks, performed on command. Personnel must wear protective clothing and decontaminate	.9975	1
6.7 Disconnect trailer vent hose		area upon completion of these tasks.	.9975	1
7.1 Check fuel temperature	5	A precise task requiring checking and recording temperature level of fuel in RSV. No communications link required.	.9825	2
7.2 Check system condition	10	A precise task requiring training and system familiarization.	.9500	2
7.3 Place system in standby mode	10	A precise task requiring training and system familiarization.	.9500	2
8.1 Open RSV fill valve	2	Simple manual task	.9978	1

[3 Additional Pages of Task Analysis Material Were Provided.]

SESSION 5

Instructions To Participating Engineers

In this session I will ask you to consider the preventive maintenance requirements of the PTPS. These are listed on your new RAS sheet. (Figure 8).

The following general information concerning preventive maintenance is available:

1. Organizational maintenance of the propellant transfer system consists of periodic visual inspection of all piping systems including valves, controls and instrumentation; operating the pumps for a short period of time and lubrication if necessary; and inspection and cleaning of filter elements.

2. Field maintenance includes replacing or repairing defective lines, valves, hoses, pumps, motors, controls, and refastening of loose piping and equipment.

3. Depot maintenance will include major repairs to pumps, motors, and other machinery as well as major repairs to controls and instrumentation.

Notice that these functions involve the whole range of preventive maintenance functions: calibration, inspection, verification of accuracy, checkout and lubrication.

Under the personnel section of the RAS we have listed the major tasks to be performed by personnel maintaining the PTPS.

You will be asked to do two things in this session: (1) make a functional flow diagram of the functions involved in performing preventive maintenance; (2) describe all the design features you might provide to aid the maintenance personnel in performing these activities. These features should include:

a. required controls and displays;

b. special test and calibration on tools and equipment;

c. access spaces;

d. test points:

e. connections;

Figure 8 Sample Requirements Allocation Sheet (Maintenance)

Requirements Allocation Sheet	Subsystem PTPS Functional Flow Dsg No. Maintenance		End Item Identification		Personnel & Training Equipment Reqmt				Tech Manual Reqmt
Function Name & No.	Design Reqmt	Facility Design Reqmt	Nomenclature	Design Form or Fig. 2. No.	Tasks	Time Reqd (hr)	Perform. Reqmt	Tng & Tng Equip. Reqd	
1. Flow-meter Calibration	Flowmeters shall be calibrated prior to each fuel transfer - accuracy reqmt. ± 0.2%				1.1 Verify that PTPS is in standby mode 1.2 Prepare prover tank 1.2.1 Set prover tank fill valve to bypass 1.2.2 Set prover tank drain valve to closed position 1.2.3 Verify that prover tank is empty 1.2.4 Open prover tank fill valves and allow propellant to drain into system for 5 minutes 1.3 Set flowmeter totalizer to 0 1.4 Pressurize RSV to 30 PSIG 1.5 Set flow rate to 50 GPM 1.6 Start transfer pump 1.7 Perform calibration 1.7.1 Adjust FLU valve for desired flowrate 1.7.2 Verify fuel temperature stability 1.7.3 Record temperature reading 1.7.4 Record totalizer readings 1.7.5 Reset totalizer to zero				

Control No. ________ Revision ________ Date ________ Approval ________ Document No. ________ Page No. 1

f. safety provisions, etc.

Here is a checklist which might help you to remember features you may wish to incorporate in your design characteristics. If you can think of a more effective way of performing the maintenance functions, list any changes you would make. Add any maintenance tasks which you feel would be required or be desirable, even if not listed on the RAS. Remember the type of maintenance man who will be provided to do these jobs.

Before you go ahead, however, I would like the answers to a number of questions:

1. Do you have enough information to do what you have been asked to do?

2. If not, what is lacking? What information would you like to have? What information would you expect to have?

3. Is the information provided on the RAS sheets useful in performing the task?

4. Would you ordinarily expect to receive information of this type at this stage of system development? From whom? Would you generate the information yourself? How?

5. Does the checklist assist in any way?

6. If you knew the number and type of maintenance men you were going to have, would this help you in performing the task?

The following questions are asked only of experimental subjects:

1. Do you find the information on your RAS sheets under Tasks useful in performing the task? Task information was not provided to control subjects.

2. Can you apply that information to today's task?

3. What equipment design implications can you draw from this personnel information?

4. Would you ordinarily expect to receive this personnel information at this stage of system design? Earlier? Later?

MAINTAINABILITY CHECKLIST

GENERAL
1. Standardization maximized
2. Components functionally grouped
3. Console layout optimized
4. Complexity minimized
5. Self-test incorporated
6. Max. time to repair minimized
7. Tools & test equip. minimized
8. Labeling maximized
9. Weight minimized
10. Calibration requirements known
11. Repair/replace philosophy known
12. Maint. procedures known
13. Personnel requirements minimized
14. Trade-offs documented

HANDLING
1. Equipment lifting means employed
2. Equipment base reinforced (fork-lift app.)
3. Drawer & panel handles employed
4. Assembly handles employed
5. Console castors employed (as applicable)
6. Damage susceptibility minimized
7. Weight label on console

EQUIPMENT RACKS-GENERAL
1. Drawers on roll-out slides
2. Panels hinged
3. In-position maintenance possible
4. Cables connected with drawers extended
5. Permanent cable inlets on front avoided
6. Heaviest items on bottom
7. Operator panels optimum position
8. Air intake & exhaust provisions adequate

PACKAGING
1. Plug-in components employed
2. Component stacking avoided
3. Accessibility based on replacement freq.
4. Wrong installation of unit prevented
5. Modules & mounting plates labeled
6. Guides used for module installation
7. Interchangeability incorporated

PANEL DISPLAYS/CONTROLS
1. Controls standardized
2. Controls sequentially positioned
3. Controls properly spaced
4. Controls adequately labeled
5. Controls adjacent to applicable display
6. Ruggedized meters employed
7. Meters externally removable
8. Panel lighting employed
9. Indicator lights "press-to-test"
10. Fuse requirements satisfied
11. Spare fuses provided
12. Warning lights employed-critical functions
13. Color of indicator lights adequate
14. Controls placed by frequency of use

TEST POINTS
1. Located on front panel
2. Functionally grouped
3. Adequately labeled-number & signal value
4. Internal test points accessible
5. Degree of test indicated
6. Adequately protected
7. Adequately illuminated
8. Located close to applicable control

ADJUSTMENTS
1. Adjustment points accessible
2. Periodic adjustments known
3. Interaction effects eliminated
4. Adjustment locking devices provided
5. Factory adjustments specified
6. Adjustment points adequately labeled
7. Fine adjustments through large movements
8. Built-in jacks for meter calibration
9. Clockwise adjustments for increasing values

PARTS/COMPONENTS
1. Arranged in family groups
2. Adequately labeled
3. Adequately spaced for tool access
4. Individual parts directly accessible
5. Delicate parts adequately protected
6. Not vulnerable to excessive solder heat

FASTENERS
1. Quick release fasteners employed
2. Fasteners standardized
3. Quantity of fasteners minimized
4. Hexagonal socket-head fasteners used
5. Captive nut & screws employed
6. Minimum number of turns required

CABLES
1. Cables fabricated in removable sections
2. Cables routed to avoid sharp bends
3. Cables routed to avoid pinching
4. Protection for cables routed thru holes
5. Cables identified
6. Cable clamping support adequate
7. Handhold & step prevention considered

CONNECTORS
1. Quick disconnect variety
2. Connector spacing adequate
3. Labeling adequate
4. Connectors keyed
5. Connectors standardized
6. Spare pins provided
7. Male connectors capped
8. Receptacles "hot" & plugs "cold"
9. Moisture prevention considered

ACCESSIBILITY
1. Access doors provided
2. Access doors self-supported
3. Access doors labeled
4. Access openings adequate in size
5. Access fasteners minimized
6. Special tools minimized
7. Component accessibility adequate
8. Guides for dangerous accesses considered

ENVIRONMENT
1. Temperature & humidity ranges considered
2. Illumination adequate
3. Transportability conditions considered
4. Mobility conditions considered
5. Storage conditions considered

SAFETY
1. Electrical outlets/junction boxes labeled
2. Interlocks employed
3. Fuse & circuit breaker protection adequate
4. Warning decals adequate
5. Guards & safety covers-high potentials
6. Protruding devices eliminated
7. External metal parts adequately grounded
8. Drawer/panel/structure edges rounded
9. Tool use considered

RELIABILITY
1. Allocated MTBF known
2. Fail-safe provisions incorporated
3. Critical/service life considered
4. Wear-in/wear-out cycles considered
5. Failures traceable by test

When reviewing layouts/drawings, this checklist may prove beneficial in covering various design features applicable to maintainability. The items or categories listed are in most cases backed up with more detailed questions based on specific criteria. The list is so designed that the answer to each item (as applicable) should be "yes".

REFERENCE DOCUMENTS SPECIFYING GOOD MAINTAINABILITY CRITERIA

NAVSHIPS 94324, Maintainability Design Criteria Handbook for Designers of Shipboard Electronic Equipment
ASD-TR-61-424, Guide to Integrated System Design for Maintainability

SESSION 6A

Instructions For Participating Engineers

In this session no further equipment inputs are available. However, the Personnel Subsystem Group has provided two (2) time-line analyses, one for operations, one for preventive maintenance, for the two major fueling functions, fuel transfer to the RSV, and fuel transfer from the RSV to the SLV. [Control subjects did not receive time-line analyses.] (Figures 8A and 9A).

These time lines analyses represent the human performance requirements pertinent to the PTPS. Major functions are described in terms of the time required to perform that function and the combination of personnel necessary to successfully complete the functional requirements of the system.

Functions are listed down the left hand column with the required personnel indented under the particular function. Time requirements for the particular functions are represented incrementally to the right of the task.

Your task today is composed of several parts:

1. Examine the time-line analyses. Note that they give you the Personnel Subsystem Group's concept of the types of PTPS personnel required and the length of time each of their tasks should take. The time-line analysis can also be interpreted in terms of the number of personnel needed.

2. Using this information and any of the inputs you received previously, indicate how many control and/or display panels you would need to operate and maintain the system. A panel is defined as any physical space specifically designed to contain two or more controls or displays. Please indicate also in what location they would be found.

3. Indicate the operating and maintenance functions to be performed by each control/display in the panel. Provide a rough layout of the panel. [Definition of rough layout follows.]

In addition, we would like answers to the following questions:

1. Do you have enough information to draw rough layouts of the control/display panels?

Figure 9
Time-Line Analysis Sheet (Top Level)

TIME LINE SHEET	Function: Propellant Transfer and Loading
	Functions & Corresponding Personnel
	TASKS
Transfer	1.0 Connect Propellant Transporter to fixed base propellant transfer system
	2.0 Transfer Propellant from Transporter to the RSV(S)
	3.0 Drain, purge, and decontaminate lines, equipment and hardstand
	4.0 Condition fuel
	5.0 Drain, purge, and decontaminate lines, equipment and conditioning unit
Loading	6.0 Perform SLV tank purge and leak check
	7.0 Connect Propellant Transfer umbilicals
	8.0 Transfer propellant from RSV to SLV, Stage I
	9.0 Monitor propellant transfer
	10.0 Transfer propellant from RSV to Stage II
	11.0 Monitor propellant transfer
	12.0 Drain, purge, and decontaminate propellant system
	13.0 Secure system

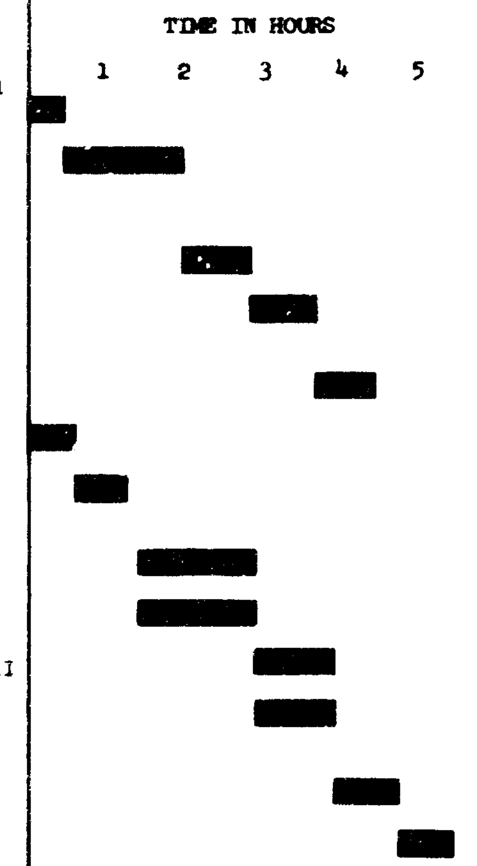
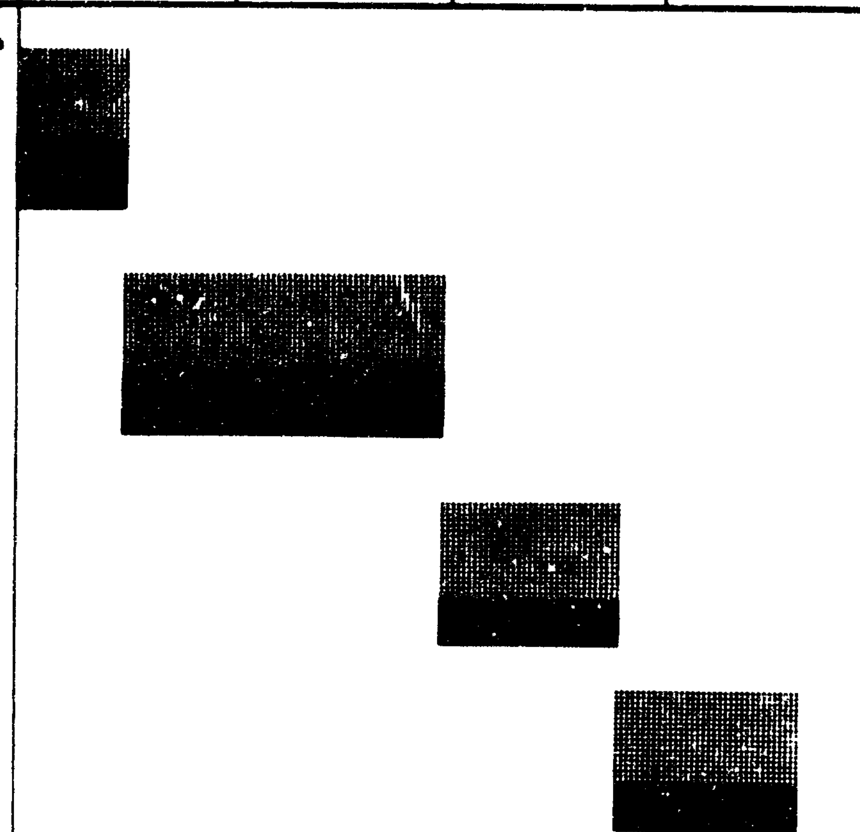


Figure 10
Time-Line Analysis Sheet (Detailed Level)

TIME LINE SHEET	Function: Propellant Transfer	
	Functions & Corresponding Personnel	
	TASKS	TIME IN 10-MINUTE SEGMENTS (1, 2, 3)
	1.0 Connect Propellant Transporter to fixed base propellant transfer systems LFMS/T #1 LFMS/T #2 LFMS/T #3 LFMS/T #4 FBS/T #1 FBS/T #2 FBO	
	2.0 Transfer propellant from Transporter to the RBV(S) LFMS/T #1 LFMS/T #2 LFMS/T #3 LFMS/T #4 FBS/T #1 FBS/T #2 FBO	
	3.0 Drain, purge, and decontaminate lines, equipment and hardstand LFMS/T #1 LFMS/T #2 LFMS/T #3 LFMS/T #4 FBS/T #1 FBS/T #2	
	4.0 Condition fuel LFMS/T #1 LFMS/T #2 LFMS/T #3 LFMS/T #4 FBS/T #1 FBS/T #2	



2. If not, what information should you have? What information would you realistically wish to have?

3. What information about personnel operations which you have not received in previous sessions would you want to have?

4. What previous information about personnel operations is relevant to and would assist in your laying out the control/display panels?

The following questions are asked only of the experimental group:

5. Do you have any difficulty interpreting the time-line analyses?

6. If so, what are these difficulties?

7. Does the time-line analysis provide you with any information you do not already have?

8. Can you tell me in a few words what information the time-line analysis provides you?

9. Do you agree with the personnel types and time requirements indicated on the analyses?

10. If not, why? What changes would you make? Why?

11. Is the time-line analysis information relevant to your task of drawing the panels? Does that information assist you in making these drawings?

12. Does the time-line analysis information have any application other than to the task you have today? Could you have used it earlier? Might it be useful later?

13. What design implications can you draw from the time-line analyses?

SESSION 6B

Instructions For Participating Engineers

In this session information has been made available by the Personnel Subsystem Group concerning the personnel who will be operating and maintaining the PTPS. This information, contained in the enclosed memorandum, contains preliminary Quantitative and Qualitative Personnel Requirements Information (QQPRI) for the PTPS. This information, broken out by the Air Force Speciality Code (AFSC) describing the job, includes position (job) descriptions and manpower estimates. There is no additional equipment information available.

If you have not completed your sketches of the control panels required in the previous session, this session will enable you to do so.

In this session we would also like you to list the individual steps required to operate the control-display equipment and to perform any other personnel operations you think necessary. List these steps in terms such as "turn on power", "monitor LN2 pressure", "open valve manually", etc. Keep in mind that safety is a prerequisite for any operation. List the steps in the order in which they should be performed. Indicate any overlapping steps. Where any step requires more than one man to perform it, please indicate the number required.

I should also like to ask you the following questions:

1. Do you have enough information at this stage of PTPS development to be able to list the operating steps?

2. If not, what information do you think you need or would want?

3. What personnel information would you ordinarily have at this stage of PTPS development? Is this information sufficient? What personnel information would you want?

4. Do you find any of the personnel information you have received previously to be useful in performing the task? If so, what information is this?

The following questions are asked of experimental subjects only:

5. Do you have any difficulty understanding the QQPRI?

6. If so, what is the problem?

7. Would you expect to receive information of this type at this stage of PTPS development?

8. Do you find the QQPRI information useful in helping you with the list of operating steps? If so, in what way?

9. What design implications can you draw from the position descriptions; from the manpower estimates?

10. Do you feel that the information contained in the QQPRI has any major impact upon your design? Would you change your design in any way because of the QQPRI?

Preliminary Quantitative And Qualitative Personnel Requirements Information (QQPRI)

To: Design Engineering Group, PTPS Project

From: Human Factors Section, Personnel Subsystem Group

Subj.: Preliminary Quantitative and Qualitative Personnel Requirements Information (QQPRI)

In accordance with the statement of work for the PTPS program, paragraph 10.3, the Human Factors Section has performed the requisite analyses and has drawn up a preliminary schedule of Quantitative and Qualitative Personnel Requirements Information (QQPRI) for the PTPS. The results of this effort are appended to this memorandum and are submitted to the PTPS Design group for its use in the PTPS design.

Analysis of the functional requirements of the PTPS within the contractual constraints imposed by the customer has allowed us to arrive at the following preliminary manpower estimate for operation and maintenance of the Titan X SLV, Propellant Transfer and Pressurization System.

Position Descriptions

The following Air Force specialities have been identified as those requiring the least amount of special training and familiarization before reaching proficiency in operation of the system.

1. Fuel Supply Officer (FSO) (AFSC 6454): will direct pre-launch operation activities.

- will assign technicians and specialists to launching crews
- will supervise propellant transfer operations from transporters to RSV's and from RSV's to the launch vehicle
- will determine fuel load for launch vehicle
- will direct emergency operations

2. Fuel Specialist/Supervisor (FS/S) (AFSC 64350B/70B): will be responsible for the receipt, storage, issue and transportation of missile fuel, oxidizers and gases. He will also accomplish routine maintenance and servicing of the PTPS. He will assist the Liquid Fuel

Systems Maintenance Specialist/Technician in propellant loading or unloading operations.

3. Liquid Fuel Systems Maintenance Spcialist/Technician (LFMS/T) (AFSC 56850B/70B): will be responsible, under the direction of the Fuel Specialist/Supervisor, for the conduct of propellant loading and unloading operations at the launch site, including emergency or damage control activities if required.

<u>Manpower Estimates</u> [For low skill, high number subjects only]

Position	Number Required
Fuel Supply Officer	1
Fuel Specialist/Supervisor	3
Liquid Fuel Systems Maintenance Specialist/Technician	8
Total Complement PTPS Operations and Maintenance	12

<u>Manpower Estimates</u> [For high skill, low number subjects only]

Position	Number Required
Fuel Supply Officer	1
Fuel Specialist/Supervisor	2
Liquid Fuel Systems Maintenance Specialist/Technician	6
Total Complement PTPS Operations and Maintenance	9

SESSION 7A

Instructions For Participating Engineers

In this session we would like you to analyze the potential operating problems which might be encountered after the PTPS system is put into use. The reason for doing such an analysis is that you may be able to include in your design certain features which might prevent the occurrence of such problems. Your list of operating problems should contain the following:

1. Description of the problem in one or at most two sentences;

2. Severity of the problem in terms of its consequences for completion of propellant transfer and safety of personnel. We suggest the following categories which you can abbreviate as A, B or C:

   A. Catastrophic -- extreme danger to system and/or personnel;

   B. Serious -- failure to complete propellant transfer;

   C. Minor -- maximum effect is delay in completion of propellant transfer.

3. Description of anticipated consequences to PTPS operation in one or two sentences;

4. Design recommendations to reduce likelihood of error occurrence.

To help you in this job the preliminary QQPRI given you in the previous session has been considerably expanded (Figure 10A) to include:

1. A list of duties and tasks for each Air Force Speciality Code (AFSC) together with the potential personnel errors that might be made;

2. The performance reliability associated with these tasks;

3. The skill level estimated to be required for each task;

4. A description of the job required of each AFSC, including the skills involved;

5. The training required to make each individual proficient.

[QQPRI given only to experimental subjects.]

Figure 11 Sample QQPRI Sheet

POSITION TITLE: Liquid Fuel Systems Maintenance Specialist/Technician

Air Force Specialty Code (AFSC) 56850B/70B

Duties & Tasks	Perf. Reliab.	Skill Level	Skill Type/Proficiency Availability	Training Requirements	No. Req.
1. Connect propellant transporter(s) to fixed base propellant transfer system Possible Human Errors - Cross - connection of hoses - Mis-alignment of coupling	.9975	5	1. Position Summary The LFMS/T is responsible, under the direction of the Fuel Specialist/Supervisor, for the conduct of propellant loading and unloading operations at the launch site, including emergency or damage control activities if required. He decontaminates the surface area, the launch duct or the sump, or the rocket as required. He directs emplacement and removal of mobile PTS equipment and seals fixed portions of the PTS. LFMS/T's assigned to maintenance teams perform unscheduled maintenance on PTS fixed equipment at the launch complex. Any LFMS/T's performing PTS procedures at the launch complex should know both the emergency and normal loading and unloading procedures. 2. Environment a. Launch Site (1) The LFMS/T controls traffic into and from the launch complex security area. He directs positioning of propellant transporters and the interconnecting of PTS elements. He performs the pre-operational checks of the PTS and conditions propellants prior to the conduct of propellant transfer operations. He controls the transfer of propellants by operating and monitoring the PTS control unit and determines when the missile has an adequate propellant load. After the transfer operation he purges the PTS and disposes of fuel or oxidizer residues. He directs decontamination activities and emergency or damage control procedures. (2) The LFMS/T performs scheduled maintenance of the propellant transfer equipment in the launch area by inspecting lines, pumps, valves, instrumentation (indicators and controllers) and system plumbing; inspecting and cleaning filter elements and strainers; recording temperature and pressure in missile tanks; removing and replacing components and parts on a time interval replacement basis. He also performs scheduled maintenance on the propellant transfer control unit.	The training should be designed to train selected Air Force personnel to: 1. Operate control panels to determine malfunctions in the propellant transfer system. 2. Perform interconnections of the electrical and mechanical mobile equipment. 3. Operate and maintain the propellant transfer system components and the various items of GOE/GSE including the propellant transporters, propellant holding tanks, nitrogen storage tanks, and propellant transfer control unit. 4. Perform emergency unloading procedures for the PTS. 5. Inspect storage tanks, disconnects, valves, piping, pressure regulators, filters, pressure gages, and temperature gages for leakage, corrosion, damage, and wear; also solenoids, relays, switches, chassis of the transfer control panel, sensors, amplifiers, motors, terminals, interconnecting cabling and instrumentation for proper operation. Instruction should include removal and replacement procedures for the above listed items. 6. Perform bench maintenance on disconnects, valves, pressure controllers, pumps, and pressure regulators in the propellant transfer system and the GOE/GSE listed above. 7. Preset the variables in the system such as pressure regulators and valve controllers, decontaminate the components and prepare them for storage or installation. 8. Perform safety and first-aid procedures and practices associated with the hazards involved in handling storable propellants, cleaning agents and high pressure gases. Approximate time required for additional training is estimated at approximately ten weeks.	
2. Prepare to transfer propellant from transporter(s) to ready storage vessels (RSV's) - Valves in system left open - System not completely tied - RSV vents not opened	.9960	[illegible]			
3. Transfer propellant from transporter(s) to Ready Storage Vessels (RSV's) - Leaks in system due to improper connection or maintenance - Failure to close valves when transporter is empty - Failure to maintain sufficient blanket pressure	.9978	[illegible]			
4. Terminate transfer operation - Carelessness in draining and purging system - Overfilling of RSV's	.9994	[illegible]			
5. Place system in standby mode - Failure to set all valves to standby - Failure to purge all propellants from the system	.9978	5			
6. Decontaminate transfer area and equipment - Failure to remove all traces of propellant from the equipment and area	.9975	[illegible]			

I would like to ask the following questions:

1. Do you have enough equipment information at this stage of PTPS development to be able to list the potential problems? Enough information about PTPS personnel and their operations?

2. If not, what information do you think you need or would want?

3. What personnel information would you ordinarily have at this stage of PTPS development? Is this information sufficient to be able to list the potential problems? What personnel information would you want?

4. Do you find any of the personnel information you received in previous sessions helpful in making up the list of problems? If so, what information is this?

5. Can you say whether more of these operating problems are equipment-initiated than personnel-initiated?

6. As a result of listing the operating problems, would you change your design in any way? Add or delete anything?

7. Could you solve these problems without design changes?

The following questions are asked of experimental subjects only:

8. Do you have any difficulty in understanding the QQPRI?

9. If so, what is the problem?

10. Would you expect to receive information of this type at this stage of PTPS development?

For each of the categories of QQPRI information, ask the following questions:

11. Do you find the QQPRI information useful in helping you with the list of potential problems? If so, in what way?

12. What design implications can you draw from each of the items of QQPRI information?

13. Do you feel that the information contained in the QQPRI in any way influenced your list of problems? If so, in what way? Would it have any impact upon your design?

At the conclusion of the session the investigator will concentrate on a review of the potential operating problems to determine:

a. Why the engineer feels it is a problem;

b. Whether the existence of the problem will in any way affect his design;

c. What information he feels he should have in order to resolve the problem.

SESSION 7B

<u>Instructions To Participating Engineers</u>

This session should be considered as a continuation of the previous one. Consequently, there are no new inputs available to you. If you have not finished your review of your design in relation to the QQPRI furnished you previously, please do so. This review will assist you in performing your major task today, which is to supply as complete list of all the hardware you would include in the PTPS as you can. In making up this list, please include the following:

1. Type of component (e.g., globe valve, flex hose, filter, fluid, press);

2. Location of component (e.g., SLV vent to PLU line, RSV #1 return line);

3. Component function (e.g., shut off valve, drain valve, filter, emergency relief).

We would also like you to flag each component which would be directly <u>operated</u> (not maintained) by PTPS personnel. Do not flag components which function only indirectly as a result of some personnel activation (e.g., the operation of a filter which results from personnel initiating fuel transfer). The flagging of components in terms of personnel operations will help us to define the impact of personnel on system design in terms of the percent of components related to personnel operations.

While it is desirable that your list be as complete as possible, it is unnecessary to break the list down to a level of detail which includes individual nuts and bolts. Where you know or can guess, you should include major components internal to a higher order assembly (e.g., pump in a PLU). The information you provide should be such that a pricing specialist can take the list and make "ballpark" estimates of the cost of your subsystem design.

SESSION 8

Instructions For Participating Engineers

As sometimes occurs during system development, the System Project Office (SPO) monitoring that development may impose changed requirements upon the contractor. The memorandum you have just received indicates that the original statement of work provisions (paragraph 7.1) regarding the number and composition of the PTPS work force have been changed. The SPO therefore requires you to examine your subsystem design to determine whether you can modify that design to meet the changed requirements. Note that the basic functions of the PTPS remain unchanged and your design must still accomplish those functions.

Your task today will require you to review the engineering and personnel inputs you have received to date. As you do so, list the following on a sheet of paper:

1. All changes in equipment requirements and characteristics which will permit the desired changes in number and type of personnel.

2. All changes in operating procedures.

3. All changes in control-display hardware.

In each case, the reason for the change and its anticipated impact upon personnel performance and crew composition should be noted.

Before you begin your review, however, I should like to ask the following questions:

1. Is it clear what you are being asked to do? If not, what would you like to know?

2. Are the changed personnel requirements reasonable, in your opinion?

3. Do you have enough information to perform the task?

4. If not, what equipment information do you think you need?

5. What personnel information do you think you need?

Redirection of Design Effort

[The following was provided to the high skill, low number subjects (Group I)]

_______________, 1967

To: Chief Engineer, PTPS Project

From: Project Officer, Titan X SLV Project

Subj.: Redirection of Design Effort

Ref.: Statement of Work, Air Force Contract 423-647C-1-67

1. Reference statement of work (paragraph 7.1) requested that the contractor design and develop the Titan X SLV propellant transfer and pressurization subsystem (PTPS) for operation and maintenance by a small number of highly trained Air Force specialists. In any design situation in which skill level and number of personnel had to be traded off, it was desired that the criterion of minimum number of personnel was to take priority. This has resulted in a PTPS design which, in the opinion of this office, tends to make excessive demands on the availability of skilled Air Force specialists.

2. It is therefore directed that the contractor examine the present PTPS design configuration and recommend such changes as will permit the subsystem to be operated and maintained by personnel requiring a minimum amount of training and skill in the performance of their duties. Although it is recognized that any reduction in the training and skill level of operational personnel may require an increase in system manning, any such increase should be kept to a minimum consistent with the safe and efficient performance of the PTPS. The total composition of the PTPS crew should not exceed N. [Variable number adjusted to each designer's original manning estimate.] All non-supervisory personnel should have no higher than a "5" level skill rating, with 50% of the group to be composed of "3" levels. Basic PTPS functions and performance requirements shall not be affected by any proposed design changes. Moderate cost increases will be permitted but must be specified in detail and shall be acceptable only where a design change is warranted by its effect on crew composition.

3. Within 30 days, therefore, the contractor will supply this office with a memorandum listing those aspects of system design which he feels can be modified to reflect the revised personnel requirements.

4. The following design factors shall be considered in your analysis:

a. the allocation of functions between equipment and personnel;

b. the design of controls and displays;

c. operating procedures;

d. safety precautions;

e. the speed with which PTPS operations can be performed;

f. requirements for auxiliary test, maintenance and instrumentation equipment used by personnel.

Major design modifications, together with their predicted effects, shall be described in detail.

5. The above redirection constitutes an addition to the scope of the referenced contract. Estimates of the cost required to perform the above analysis shall be supplied to Mr. Robert B. Polhemus, Titan X SLV Contracting Officer. Technical questions shall be referred to Major David Jones, Assistant Project Officer, Titan X SLV project.

By direction ____________________

Edward B. Rothermere
Col., USAF
Project Officer
Titan X SLV Project Office

[The following was provided to low skill, high number (Group II) subjects.]

________________, 1967

To: Chief Engineer, PTPS Project

From: Project Officer, Titan X SLV Project

Subj.: Redirection of Design Effort

Ref.: Statement of Work, Air Force Contract 423-647C-1-67

1. Reference Statement of Work (paragraph 7.1) requested that the contractor design and develop the Titan X SLV propellant transfer and pressurization subsystem (PTPS) for operation and maintenance by Air Force personnel who would require a minimum amount of training and skill in the performance of their duties. The requirement for minimum skill level was considered to have priority over other manning criteria, including the number of personnel required.

2. An analysis of Air Force manning resources has indicated that a substantial number of skilled personnel in the speciality codes required by the PTPS will be made available for this program by the progressive phasing out of earlier Titan models. In view of this development it may be possible to achieve reductions in the total size of the PTPS manning by making appropriate design modifications reflecting the changed nature of personnel requirements. As a design goal, it is requested that the contractor examine the possibility of manning the PTPS with a total of N personnel. [Variable number adjusted to each designer's original manning estimate.] It is anticipated that all PTPS personnel will have not less than a "7" level skill rating.

Basic PTPS functions and performance requirements shall not be affected by any proposed design changes. Moderate cost increases will be permitted but must be specified in detail and shall be acceptable only where a design change is warranted by its effect on crew composition.

3. It is therefore directed that the contractor examine the present design configuration of the PTPS and recommend such changes as will permit the subsystem to be operated and maintained by a small number of highly skilled Air Force personnel. The primary criterion in proposing design modifications shall be the reduction of manpower, consistent with the safest and most efficient performance of the PTPS.
[Remainder of memorandum includes same material as previous memorandum.]

SESSION 9

Instructions For Participating Engineers

In this session we are going to deviate a little from our previous procedure by giving you a number of special problems to solve.

1. Administer item 10 of Test II as described in Meister and Sullivan, 1967. See Table 13 in this report for specific sub-items.

2. I want you to review mentally the various items of information I gave you during your subsystem design these past weeks. Here is a deck of cards, on each of which one of these inputs is described. Take the cards (the investigator will shuffle them first) and look at each one carefully in order. After you have looked at each card, I want you to arrange them in the order in which you consider each item of information to have been valuable, useful to your design. In other words, place the card with the most useful input first, the card with the next most useful input next, and so on for each card. [See Table 10 in this report for specific items.]

After the engineer sorts the cards, review with him the reasons why he sorted them in this way. Emphasize the following points:

a. Did the input provide any useful information;

b. Did the input have any effect on your subsystem design; if not, why;

c. Was the sequencing of the input appropriate.

3. Ask the engineer to pick out which of these inputs he would wish to have at the very start of design. Why?

4. I would like you to think now of two design situations, in both of which you are to design a propellant transfer subsystem something like the one you have just finished designing. In the first situation you will design for your own Marquardt technicians. In the second situation you will design for Air Force personnel who have had no prior experience in propellant transfer work, but who will be graduates of a 3 months Air Force course in missile operations. The subsystem shall be designed so that the Air Force personnel can operate and maintain the subsystem without any Marquardt assistance or consultation. In every other way the design requirements (e.g., reliability, duration of the operating cycle, etc.) are the same for the two situations.

Assume no restrictions imposed by cost. Primary design criteria are safety and completion of propellant transfer to mission requirements.

We want to know what difference, if any, the differences in personnel would make to your design. Here is a list of subsystem design characteristics. Put a check mark in either or both columns, depending on whether you would include a particular characteristics in your subsystem design. You may of course include the same characteristic in both subsystem designs or in either.

DESIGN CHARACTERISTICS	MARQUARDT	AIR FORCE
1. All operations performed from a central control station.		
2. Some valves manually operated, others automatically.		
3. All operations are computer controlled; personnel functions are restricted to starting the operation and stopping it in case of malfunction.		
4. Multiple redundancy built into all valves and other major equipment units.		
5. Automatic sensors built into all valves, control units, RSV's, etc. which will adjust or stop flow when preset values are reached or an out of tolerance condition arises.		
6. Schematic display of all valve positions and flow conditions.		
7. Only critical valve positions and flow conditions displayed.		
8. No displays except a master malfunction legend light.		
9. All operations performed from fuel carts which must be connected and disconnected as required.		

10. Built in test equipment which automatically senses out of tolerance conditions, localizes the malfunctioning unit and displays that unit location.

11. Manual calibration of major control units (e.g., flowmeters) required prior to operation of subsystem.

12. Calibration of major control units (e.g. flowmeters) performed automatically prior to subsystem operation.

13. Continuous personnel monitoring of individual meters describing propellant flow.

14. Manual adjustment of valve controls to make final "topping" adjustments to propellant in rocket tanks.

15. Other (to be supplied by subject, when he feels that other design differences would exist).

After the subject has completed this item, review with him the reasons for his choices.

5. You have been given the task of designing a propellant transfer subsystem to be manned by Air Force technicians about whom you know nothing. Here is a list of items of information which might or might not be of use to you if they were included in the statement of work. Rank these factors in order of their importance to equipment design and the degree to which they should influence you as the designer. [See Table 11 for specific items.]

SESSION 10

Instructions For Participating Engineers

Today's session will involve a series of problems similar to the ones you received in the previous session.

1. We will begin by asking you to design a propellant transfer system to the same functional requirements as the ones listed in your original statement of work. There will be, however, one major difference. One of the requirements is that the system must be operated and maintained by two Air Force personnel as a maximum. No further information about these personnel is available. Cost should be a consideration in your design, but not the primary one. You should take advantage in your design of all state-of-the-art advances.

We wish you to analyze (in as much detail as possible) the design requirements for such a system. In particular we would like to know what special equipment characteristics and modifications to your original design would be required to insure its operability by two people.

a. In designing this system, what were the major items of information you felt you needed and did not have?

b. You will be given a set of cards to sort. These cards contain some of the items of information you might want to know in order to develop an appropriate design for the system. We want you to rank these items in the order of importance you feel they merit in terms of enabling you to develop the most efficient design. Thus, the first card you would place on the table would be the most important, the second card you would put on top of this would be next most important, etc. [See Table XII for specific items]

2. I would like to find out whether and to what degree your design would be affected by certain requirements, if these were included as part of your statement of work and no waiver were permitted by the customer. You may dislike some of these requirements but consider that they are forced on you by the customer. Assume you had the job of designing a propellant transfer system something like the one you have just finished designing. Each requirement is listed on a card; please examine them in order carefully and then sort them into three piles, one each for the following categories: design would be greatly affected; design would be slightly affected; design would not be affected at all. [See Table VIII for specific items]

APPENDIX II

DESCRIPTION OF SYSTEM EFFECTIVENESS MEASURES EMPLOYED TO COMPARE OVERALL SUBSYSTEM DESIGNS

RELIABILITY.

The reliability prediction made was based on the following requirements:

1. The prediction desired was a point estimate to four places of the probability that the system, once activated, will perform its mission without interruption. The system has two mission segments: (1) to transfer propellants from the railroad to the storage area; (2) to transfer propellants from the storage area to the rocket tanks. The two mission segments are independent, that is, propellant transfer in mission segment (1) will not necessarily be immediately followed by transfer in mission segment (2).

2. For purposes of this evaluation, a failure was defined as any equipment malfunction which prevents completion of the subsystem mission (i.e., transfer of propellants). Malfunction of any device or interlock which was required for safety but which did not physically prevent propellant transfer would also be considered as a failure, since personnel would not ordinarily be permitted to initiate or complete transfer once such a malfunction was noted.

3. The probability estimate covered an operating period of 60 hours for each mission segment.

Schematics, bills of material and operating procedures, as supplied by each designer, were reviewed and coordinated in order to determine the logical subdivision of each system into its constituent elements for which failure rates and corresponding reliabilities were available. Component failure rates were obtained from the following two sources:

Failure Rates , AVCO Corporation, Reliability Engineering Data Series, no date.

RADC Unanalyzed Non Electronic Part Failure Rate Data , Technical Report No. RADC-TR-66-828, Rome Air Development Center, Griffis Air Force Base, New York, (1966).

The general procedure for reliability prediction requires four essential steps. These are: (1) system definition; (2) system analysis; (3) model formulation; (4) model solution (quantitative results).

A more detailed description of the four steps follows:

1. System Definition

The reliability analyst analyzes the composition and configuration of the system. The system configuration includes the system envelope, its functional and physical boundaries, the objectives of the system (i.e., its mission(s)) and a definition of what constitues system failure. The latter includes alternate/degraded modes of operation.

2. System Analysis

The analyst must then investigate the system to ascertain how the constituent parts work together to provide the required functions. Certain parts will be found essential, others may have redundant counterparts and still others may not be required at all. The results of this analysis culminate in the construction of a reliability or probabilistic block diagram. This diagram graphically illustrates the functional interrelationship of equipment parts including alternate although perhaps "degraded" modes of operation. This diagram does not necessarily depict signal flow but rather the system parts that participate in each mode of operation.

3. Model Formulation

Using the probabilistic block diagram constructed in the previous step, a mathematical model is developed which permits combination of the individual equipment reliabilities into an evaluation of the overall system reliability.

4. Model Solution

Quantitative solution of the model requires determination of the reliability characteristics of the individual system elements. This can be accomplished in several ways including the use of standard failure rates, data sources or empirically derived data. Once these data are determined they are inserted into the mathematical model to obtain the overall system reliability.

Individual substeps include:

1) summation of failure rates for a group of essential, statistically independent elements and

2) conversion of a failure rate to a probability and suitable combination of probabilities where the step above does not apply.

Significant characteristics differentiating the subsystem designs, which affected the reliability predictions are listed below:

Subject N

Design encludes redundant flowmeters and a heater subsystem immersed in the RSV. Design does not include either pumps or a T.V. monitoring system.

Subject S

Design includes a recirculating heat exchanger subsystem, and a T.V. monitoring system. Design does not include redundancy for its pumps or flowmeters.

Subject J

Design includes redundant flowmeters, but lacks redundancy for its pump(s) and does include a recirculating heat exchanger. Otherwise extremely similar to Subject N.

Subject D

Design includes redundant flowmeters, a T.V. monitoring system, and a recirculating heat exchanger system; does not include redundancy for its single return pump, and does include a large multipoint temperature recorder.

Subject H

Design includes redundancies for all major components in the system such as pumps, flowmeters, computer, RSV tanks, etc. The design is also distinguished by being the only totally automatic system designed.

Subject K

Design is distinguished by the large number of components called

out, the T.V. monitoring system, and its redundant pumps and flowmeters.

BASIC DATA FOR COST ANALYSIS

TABLE XIV

Distribution of Costs Among the Six Subsystems

($ x 1,000)	Subjects					
	J	N	S	D	H	K
1) Tanks	240	200	220	200	240	250
Temp. Controls	75	25	45	75	75	75
Dump	20	20	20	20	20	35
Flowmeter Prover Sys.	50	35	50	50	40	None
	385	280	335	345	375	360
2) Mechanical Hardware	215	215	164	215	284	288
Pumps	-	-	40	42	81	180
	215	215	204	257	365	468
3) Electrical & Instru.	69	30	30	85	86	50
Computer	-	-	-	-	300	-
	69	30	30	85	386	50
4) Major Elect.	18	18	25	25	25	35
5) Console	12	10	10	12	15	12
Display	-	-	-	-	20	-
	12	10	10	12	35	12
6) Racks, trays, etc.	8	5	5	8	12	5
Total	707	558	609	732	1,198	930

SAFETY EVALUATION CRITERIA

1) Personnel will be provided with the best available protective clothing and respiratory equipment and safety protective systems.

2) Potential personnel exposure is ideally nil, except that two operations cannot within mechanically feasibility be made remote, viz.; connect and disconnect of road vehicles carrying propellants, and connect and disconnect of flight vehicles.

3) Propellant dumps, bleeds, drains, discords, etc., are not released to the atmosphere, but are contained in a closed vessel thus eliminating gross atmospheric pollution and providing for disposal or reprocessing under controlled conditions.

4) Propellant and pressurant vents are processed through a chemical solution which processing renders inert the toxic gases.

5) Propellant flow lines and systems are assumed to provide adequate design safety factors as provided in applicable codes. This assumption applies to all "code" items such as electrical, electronic, deluge and shower systems, fire and heat sensors and warning devices.

6) Manual operations, ideally, are reduced to a minimum so that human error as well as personnel exposure is minimized.

7) Repairs and maintenance as required is scheduled at non-critical time and under conditions that paragraphs (2) and (3) are complied with to a maximum degree.

8) All propellant wetted items are assumed to be of maximum propellant compatability insofar as selected materials of construction are concerned.

9) Site utilization and layout will comply with the applicable DOD instructions which will dictate utilization.

APPENDIX III

EXAMPLES OF DESIGN OUTPUTS DEVELOPED BY SUBJECTS

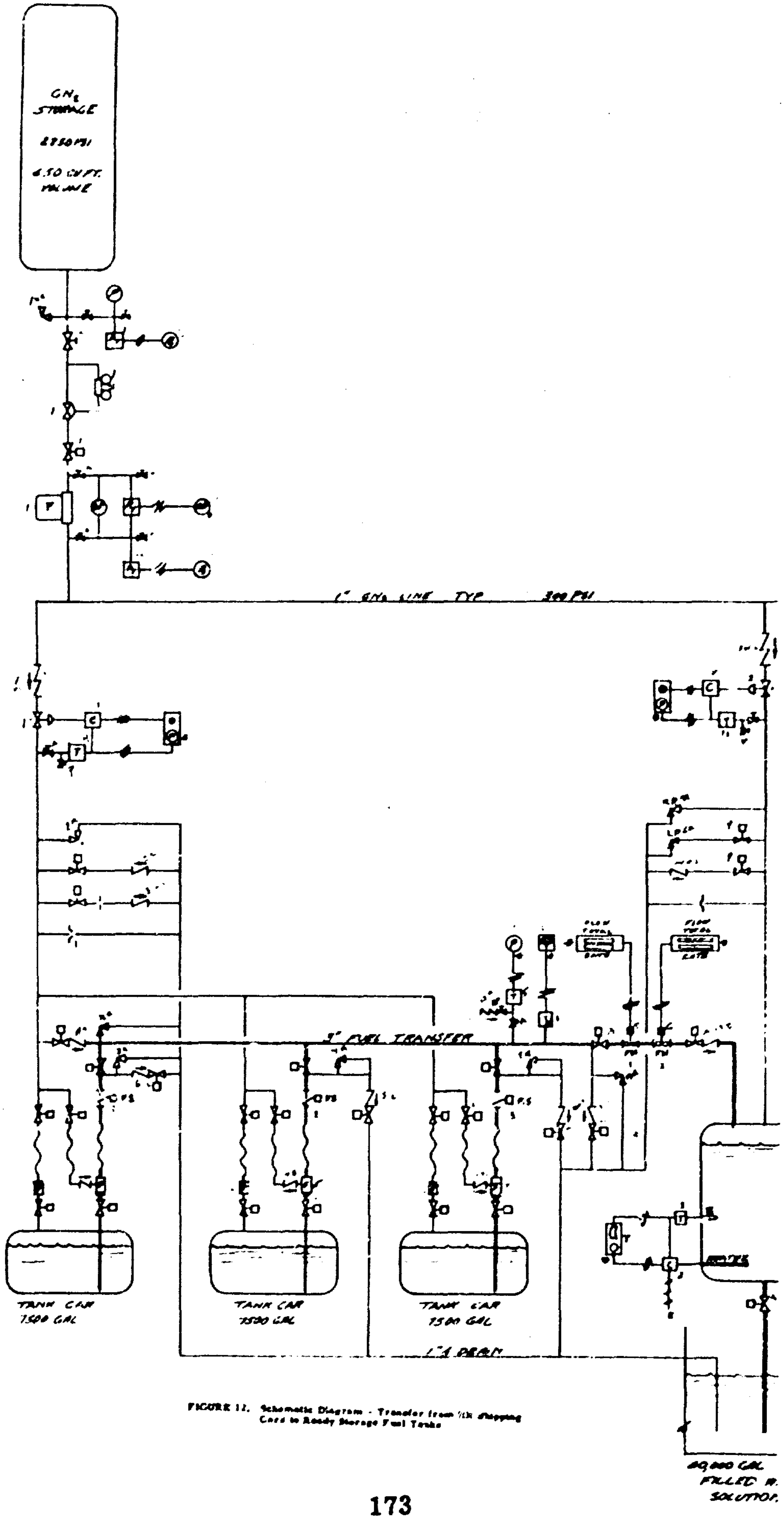


FIGURE 12. Schematic Diagram - Transfer from [illegible] Shipping Cars to Ready Storage Fuel Tanks

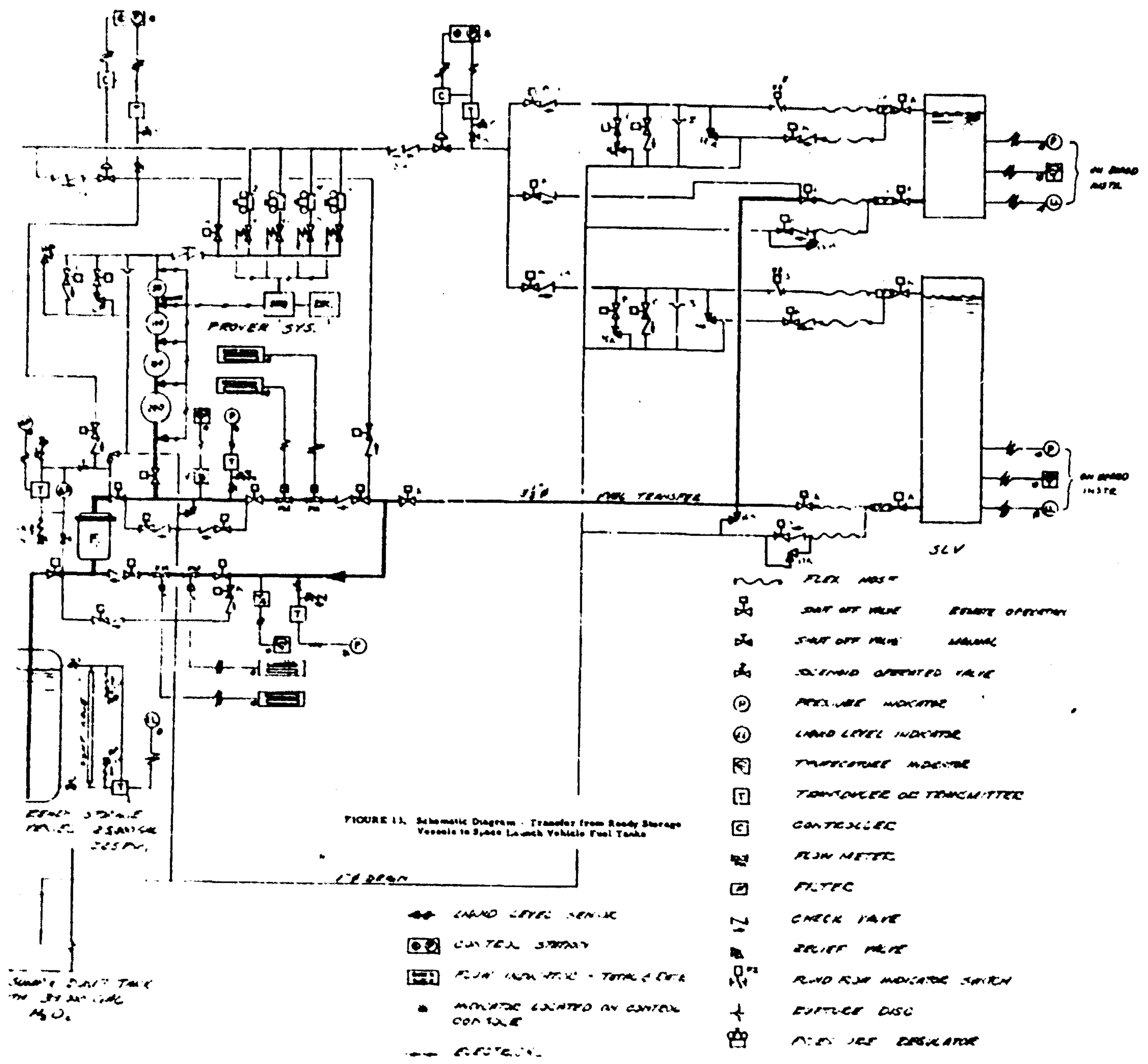


FIGURE 13. Schematic Diagram - Transfer from Ready Storage Vessels to Space Launch Vehicle Fuel Tanks

TABLE XV. EQUIPMENT DESCRIPTION NOTES

3.0 INITIATE PROPELLANT TRANSFER

3.1 START FUEL FLOW - A remote operated fuel control panel will be activated to start the transfer pump.

4.0 MONITOR FUEL TRANSFER

Monitor via inst. recorders on fuel control panel

4.2 a) Pump inlet pressure (30 psig)
b) Pump outlet pressure (150 psig)
c) Pump RPM (?)
n) Pump discharge temp.
4.3 e) RSV liquid level (ΔP and sight glass with level transmitter)
4.1 f) Fuel flow rate - counts and gal/min.
g) Fuel temperature at meter

EQUIPMENT DESCRIPTION - PUMPING OPERATION

Flex Hose - 2" - Stainless Steel - Teflon lined, continuous helical convolution and SS wire mesh 100 psi

Filters - 2" - Mesh type - Stainless Steel Wire, 10μ 200 psi rating - locate down stream of pump discharge

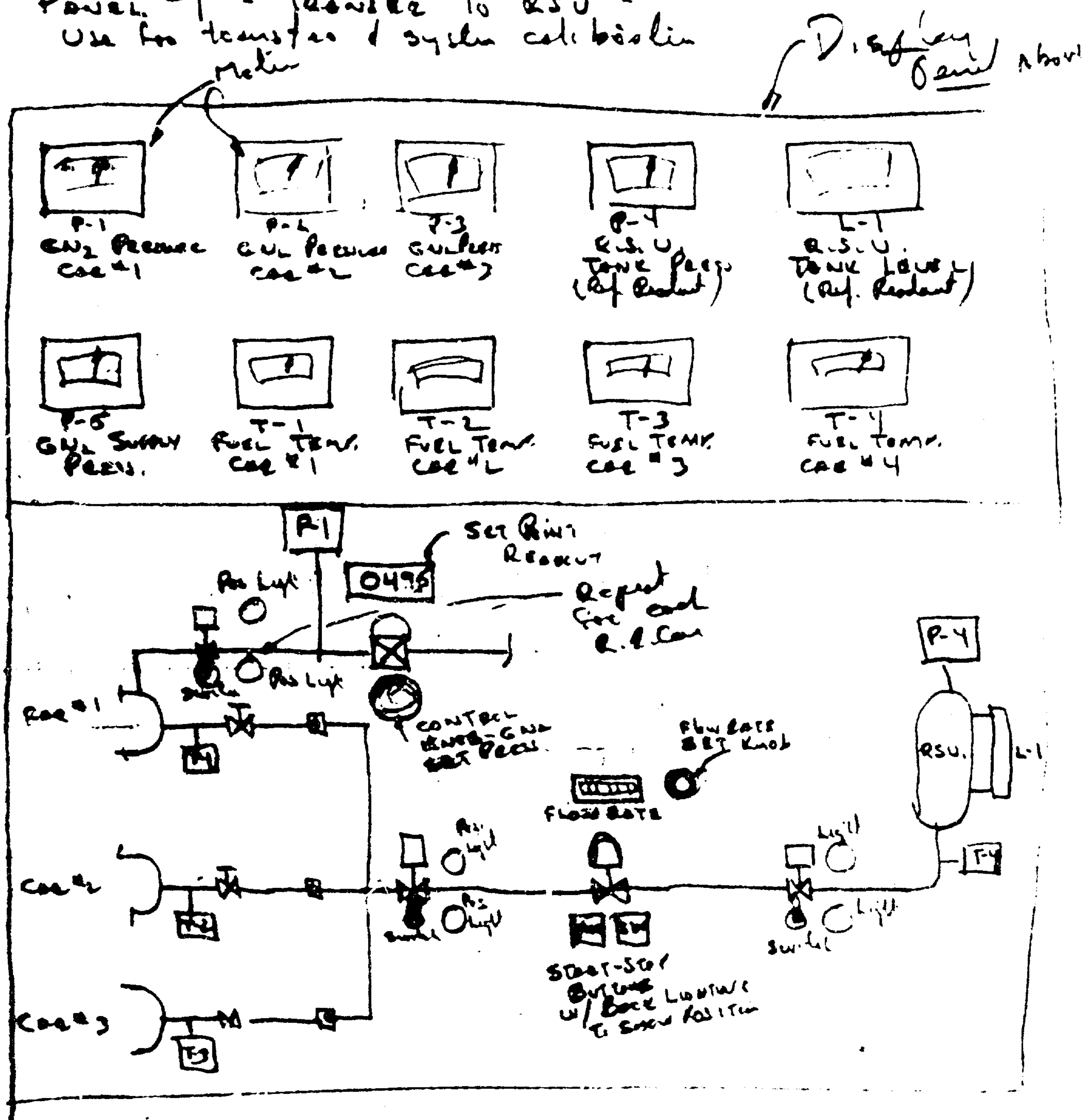
Pumps - Canned Type (Integral) no sniffing box, packing gland or mechanical seal - impeller should be mounted directly on the shaft - sleeve type shaft bearing - lubrication provided by the propellant pumped (A-50) probably 3ϕ, 60 ~, 440 volts - discharge pressure 150 psig, capacity 200 GPM

Check Valves - Swing or poppet type - low ΔP (1.0-2.0 psig)

Valves - 2,0 inch, pneumatic remote operated globe type (probably Annin Co.)

Session #? - Pg. 2

Panel #1 - Transfer to RSU -
Use for transfer & system calibration



Cont. Panel

Note: - Control Panel is schematic type panel with switches, lights & controls located at component location in panel.

FIGURE 14 EXAMPLE OF CONTROL PANEL SKETCH

TABLE XVI. OPERATING PROCEDURE

OPERATING PROCEDURES FOR TRANSFER FROM STORAGE TANKS TO SLV

6.0 Perform SLV Tank Purge and Leak Check

1. Connect SLV Flex Hoses to appropriate valves

   SLV-2-VV-1 (Vent), SLV-2-PV-1 (Press), SLV-2-FV-4 (Fill), 2nd Stack Relief Valve, SLV-1-VV-1 (Vent), SLV-1-PV-1 (Press), SLV-1-FV-4 (Fill), 1st Stack Rel. Valve

2. Check that control panel is de-energized and that all line valves are closed

3. Open all Syst. Hand Valves - RSV, Line Filters, Instrumentation, GN_2 Regulation System (use Hand Valve Check-off Sheet)

4. Energize Propellant Transfer Panel - Confirm by Energy Display Light

5. Open Valves, RSV-FV-41, RSV-FV-42, RSV-FV-51, RSV-FV-52, RSV-FV-55, SLV-2-FV-1, SLV-1-FV-1, SLV-2-FV-3, SLV-2-FV-2, SLV-1-FV-3, SLV-1-FV-2

6. Open GN_2 Valve GN_2-1 or GN_2-2, Pre-set Pressure Reg. pressurizes entire propellant transfer system

7. Monitor Gauge Pressure (system) using pump discharge pressure

8. Isolate system pressure by closing GN_2 Purge Valve GN_2-1, or GN_2-2, monitor pressure gauge. A constant drop-off in pressure will indicate system leakage. If leakage is detected, institute corrective action check-off list.

9. If Syst. Pressure Check is O.K. proceed to pressure check SLV-2 by opening valve SLV-2-FV-4 and GN_2-1 or GN_2-2 - isolate pressure by closing GN_2-1 or 2 and monitor gauge pressure for decay. If leakage is detected, institute corrective action check-off list.

10. If SLV-2 is O.K. close SLV-2-FV-4 and proceed to pressure check SLV-1 by opening SLV-1-FV-4 and GN_2-1 or 2 - Repeat Step 9.

TABLE XVII. BILL OF MATERIAL

No.	Qty.	Type of Component	Location of Component	Function of Component
14	100	Needle Valve - $\frac{1}{4}$"	Various Locations throughout system	Isolation of front end instruments
15	37	Relief Valve - 22-2" Vent Line 10-3" Fuel Line 5 -2" Cryogenic	Various Locations throughout system	Protect various tanks and lines from exceeding safe oper. limits
16	8	Pressure Regulator	GN_2 Pressure System GN_2 Purge System RSV, SLV, RR Cars, Transport Trailers	Reduce pressure from storage (6000 psi) to operating pressure
17	8	Loader (Pressure Regulator)	GN_2 Pressure System GN_2 Purge System RSV, SLV, RR Cars, Transport Trailers	Load pressure regulators above
18	119	Remote Valve (Pneumatic) 28-1" Nitrogen Valves 16-2" Vent Valves 60-3" Fuel Valves 15-1" Fuel Valves	Various locations as per schematic	Remote operated stop valve
19	119	Solenoid Valve - 4 Way 3 Position	Various Locations as per schematic	Electrical activation of pneumatic cylinder

APPENDIX IV

GUIDE TO THE DEVELOPMENT AND USE OF PERSONNEL RESOURCES DATA INPUTS IN DESIGN

Introduction

The purpose of this Guide is to describe:

(1) Those PRD inputs which are particularly relevant to equipment design

(2) What should be contained in these inputs

(3) The design implications that can be drawn from these inputs.

The Guide is directed to both Human Factors specialists and engineers. The former will want to know what and how PRD inputs should be developed; the latter will be particularly interested in how to apply these inputs to design.

Since this Appendix will deal with only those PRD inputs which might be expected to exercise an influence on equipment design, it does not pretend to be exhaustive; other inputs, of value primarily to the personnel specialist, have been treated superficially or ignored.

The developmental time span in which these inputs are developed and applied is assumed to start with the period preceding the preliminary technical development plan (PTDP) and to extend through the contractor definition (1B) phase. The reason for not going beyond Phase 1B is that, as has been pointed out previously, beyond Phase 1B the probability of influencing design significantly is very slight. Hence, the Guide covers training inputs only as specification requirements and does not deal at all with test and evaluation inputs.

This Appendix can provide, of course, only an outline and not a detailed description of each PRD input. A complete treatment of the topic would require another report as lengthy as the one describing the present study.

Much of the material has been extracted (and modified in the light of the study results from Rabideau, Cooper and Bates (1961) and for a more detailed treatment, particularly of the mission/event and task analyses, the reader is referred to these authors. The specific application of the PRD inputs to design have, however, been derived from the results of the present study.

The following analyses and inputs will be covered:

(1) Mission/event analysis

  (a) Determining system requirements

  (b) Segmenting the mission

  (c) Identifying system functions

  (d) Describing personnel functions

  (e) Describing personnel function interrelationships

(2) Task analysis

  (a) List of tasks

  (b) Task descriptions

  (c) Task sequence

  (d) Task criticality

  (e) Task duration

  (f) Task difficulty/error likelihood

  (g) Time-line analysis

  (h) Position descriptions

(3) Number of personnel required

(4) Skill descriptions

(5) Length/type of training required

(6) Personnel availability

(7) Personnel/equipment analysis

(8) Inputs required for the PTDP and RFP/SOW (Request for Proposal/Statement of Work)

Each item above contains the following information:

(1) Definition of the input

(2) What the input should contain

(3) Procedures for developing the input

(4) Developmental phase/document for which the input should be supplied

(5) Design applications

(6) Example of analytic output (abstracted from Rabideau et al. (1961) and slightly modified for purposes of this discussion)

PRD INPUT 1: MISSION/EVENT ANALYSIS

The mission/event analysis is begun at the earliest stage in system conceptualization and culminates in a series of inputs to the PTDP. The mission/event analysis makes possible basic decisions regarding the system configuration, e.g., the degree to which the system should be automated.

There are four reasons why this analysis should be performed by the Human Factors specialist: (1) to secure information which is required for the specification of personnel requirements in the PTDP, RFP and SOW; (2) to familiarize himself with the system with which he will have to work later; (3) to check the system configuration developed by the engineer to insure that it satisfactorily takes account of personnel factors; (4) to influence that system configuration by means of the personnel information he provides to the engineer.

It may appear to the reader as if very little personnel-related information can be drived at these very early stages of system development. This is not true. Few systems are complete technological innovations and much can be learned by analyzing their predecessor systems. In addition, the logic of system design comes to the aid of the personnel analyst. Assume, for example, that the system requirement is to design a Mach 2 bomber with low-level penetration capabilities. Regardless of any other special functions the system may have, the aircraft will require a pilot and co-pilot. It will have to take off, navigate to a predetermined position, release its bombs, return and land. Manifestly certain mission segments and functions are automatically implicit in the requirement. Certain cockpit controls and displays are also obviously required, e.g., altimeter, radio gear. Examination of reports describing advanced avionics concepts will help the analyst conceptualize at least a rough configuration or envelope for the aircraft. Obviously, a great deal can be deduced from basic facts.

The entire process is obviously a creative one, but it is no more creative for the personnel specialist than it is for the system engineer, except that the former may have to work harder at gathering the equipment information which may be more available to the system engineer.

Mission/event analysis is the determination of the operations which must be performed by the system in order to satisfy system mission requirements. It is a description (in verbal, graphic, tabular and quantitative form) of the events which must occur in order for the system to accomplish its stated objectives. As such, it is essential that the personnel specialist perform this analysis along with the system engineer.

Since every system requires the determination of equipment functions, a mission/event analysis will always be performed by engineers to specify the equipment characteristics of the system. This engineering analysis may or may not involve personnel factors, probably not. Although system engineers will ordinarily not perform an exhaustive analysis of the system's personnel requirements, the equipment analysis they perform may result in certain configuration decisions which determine and constrain personnel functions. The personnel specialist must examine these equipment decisions to determine what their implications for personnel functions are and whether these implications are acceptable.

Mission/event analysis is a fairly complex process. It includes a number of activities, some of which are performed concurrently, so that picking them out as individual steps (as has been done in this guide) is somewhat arbitrary and largely for convenience in discussing them. Moreover, the Human Factors specialists should realize that this analysis cannot be divorced from its equipment aspects, so that the system engineer may well have performed studies which overlap, to a certain extent, with the personnel analysis.

The outputs of this analysis will include the following, which should be included in the personnel section of the PTDP, together with supporting data extracted from the analysis:

(a) An estimate of personnel to be included in the operating/maintenance crew of the proposed system

(b) List of functions to be performed and how these are interrelated on a time basis

(c) Descriptions of tasks to be performed to the most detailed level possible

(d) List of job positions for the personnel specified, referenced to already available Air Force positions

(e) The skill level required for each job position

(f) Length and type of training required for each position

PRD INPUT 1A: DETERMINATION OF SYSTEM MISSION REQUIREMENTS

The obvious starting point for the analysis is the determination of what the system is supposed to do. Sources of information about the proposed system include data from previous systems engineering and operations analyses, the results of any preliminary feasibility studies, government documents describing development objectives, etc.

(1) The Human Factors specialist must determine whether already-established system determinants require that the system be manned and the basic functional purposes for the manning. Even if the system is unmanned, almost certainly ground maintenance functions will require personnel operations. Since the system engineer is primarily concerned about equipment, he may maintain that personnel functions are minimal, and, therefore, not worthy of detailed examination. The Human Factors specialist should in any event examine system requirements to pinpoint those areas in which personnel will be needed. The list of personnel areas he will develop should suggest--very tentatively, at this point--that certain control equipment will be needed to facilitate personnel operations. The Human Factors specialist should examine the engineer's data and reports to determine if the latter has identified those points of personnel functioning.

(2) The Human Factors specialist should determine whether these functional purposes are realistic, in the light of known human performance capabilities and limitations. For example, will a technician be asked to lift a 300-pound weight? If so, is it planned to supply the appropriate lifting equipment?

(3) He should determine the general ranges of environmental variables to which personnel will be exposed, both normally and under emergency conditions. Such variables may be acceleration, noise, temperature, etc. In addition, response requirements should be noted.

(4) He must determine what constraints, e.g., physical envelope delimiting the crew workspace, speed and accuracy requirements, etc., are imposed on the system. Could these influence the operator's performance? In what way? Has the preliminary design for the system taken account of these constraints? The Human Factors specialist should point out to the engineer the potential effects of these constraints on performance and, if these are severe limitations for personnel, determine whether alternative configurations are possible.

At this initial stage of personnel resources analysis, only a few design applications for the data can be derived. The basic purpose of this step is to gather necessary data for more detailed analysis. At the same time the examination of the functional purposes for the humans in the system, as well as the range of environmental variables, may suggest certain operational conditions under which personnel may be stressed unduly and which, therefore, require design modifications. This step will provide preliminary functional allocation data to be used later and will identify dynamic physical variables, e.g., acceleration, noise, heat, which need further analysis. Data on static physical variables relevant to the layout of workplaces, housing, access can also be gathered.

TABLE XVIII

SM-X SYSTEM MISSION REQUIREMENTS

GENERAL MISSION

Strategic Bombing of Targets Within 1200 Mile Range

SYSTEM DESCRIPTION

General:	Mid-Range Ballistic Missile
Range:	Maximum 1200 miles, minimum 400
Payload:	10,000 pounds
Propulsion:	Solid
Guidance:	Inertial. Not susceptible to ECM jamming
Launch Capability:	All missiles off ground within five minutes following strike order
Areas of Deployment:	All climatological and geographic conditions north of 45 degree N. latitude
Mobility:	Temporary site, 15 minute lead time to initiation of redeployment
Missile:	Roadable, transportable on trailer-erector vehicle.
Nature of Site:	Soft with provision of mobile living quarters for squadron personnel. Surveyed bench mark required at each site location
Logistics:	Supply from closest air base, maximum separation 200 miles. Helicopter requirement for personnel and components

MISSION REQUIREMENTS

Mission	Mission Requirements
1. Strategic Bombardment of Military, Industrial, and Urban Targets with High Yield Weapons	a. System performance such as to minimize enemy capability for: (1) Detection of missile (2) Adequate early warning and dispersal (3) Interception of missile or ECM (4) Retaliation (5) Strategic support of military

TABLE XVIII (continued)

SM-X SYSTEM MISSION REQUIREMENTS

b. Satisfactory guidance accuracy

c. Effective control of warhead burst altitude

d. Short reaction time - strike order to launch

e. Mobility of weapon system

f. Low initial dollar cost per operational missile (and associated equipment)

g. Low operations and maintenance costs

h. Moderate manpower requirements

PERFORMANCE REQUIREMENTS

Mission Requirements	Performance Requirements
Missile Flight Performance	1. Engine ignition upon firing signal 2. Acceleration and velocity per program 3. Attitude control within tolerance limits 4. Nose cone separation per program (following engine burnout)
Guidance Accuracy	1. Circular error probability (.50) radius of three miles
Warhead burst altitude control	1. Detonation at preselected altitude $\pm$ 5,000 feet
Reaction Time	1. All operational missiles launched within 15 minutes following strike order . Possible requirement for automated launch subsystem . Continuous monitoring of missile readiness required, implying need for fairly extensive display subsystem . Possible requirement for highly skilled maintenance personnel

TABLE XVIII (continued)

SM-X SYSTEM MISSION REQUIREMENTS

Mission Requirements	Performance Requirements
Reaction time (concluded)	2. Missiles continuously on alert (combat standby)
	3. Down time for maintenance not in excess of 10 percent
Mobility of System	1. Site capable of initiating redeployment within 15 minutes
	2. Total time required for site setup (to launch time) not in excess of 30 minutes

TABLE XVIII

SM-X SYSTEM CONSTRAINTS

System Constraints	Description
Dollars	Limited. Total availabe for R&D - $100 million.
Schedule Time	R&D complete by December 1960; Production by 1964.
Physical Resources	Unlimited for purposes of this system.
Availability of Manpower	Extremely limited en re AF 5 to 7 level personnel with missile and electronic AFSCs.
Environmental Programs	
Climate and Weather	Arctic, continental and marine climates as found in Europe north of 45 degrees N. Latitude. Because of alert requirements, system must be capable of all weather 24-hour operation.
Wind	System must be capable of launch in winds up to 45 mph.
Temperature and Humidity	See climate and weather.
Geography	Installation may be located on any terrain accessible by roads of less than 7% grades. Level area of finite dimensions required for site. Tundra may provide a problem. Trees may provide some cover with respect to aerial reconnaissance.
Atmospheric Composition and Contaminants	Not relevant to mobile open site and solid propellant operations.
Lighting and Audition	Lighting and auditory noise anticipated as design problems in trailer interiors. Communication system requires lines from living quarters to operations trailer. Also need alternate means of communications between wings, squadrons, and sites.

TABLE XVIII (concluded)

SM-X SYSTEM CONSTRAINTS

(concluded)

Environmental Programs	Description
Safety Hazards	Accidental detonation of warhead, premature ignition of missile power plant, toppling of erect missile, falls from work platform, electric shock. Requirement for "buddy" system may increase manpower requirements.

PRD INPUT 1B: DIVISION OF THE MISSION INTO SEGMENTS AND IDENTIFICATION OF OPERATIONAL, TASK AND ENVIRONMENTAL OPERATING PERSONNEL

Segmenting is an arbitrary process which serves as a convenience, in that it separates what may be a protracted mission period into smaller segments which are more convenient to work with in identifying and analyzing system functions. Segments should have identifiable start and end points.

An initial step in segmenting the mission is to draw a graphic profile of the mission. The purpose of profiling the mission is to describe the potential effects on personnel performance of changes in system variables throughout mission time, from a preselected starting time to some end point.

The profile consists simply of a graphic plot of the various stages of the system's use, e.g., take off, rendezvous, bomb, return, etc. The profile is plotted on a real time base --if known--otherwise a relative time base.

The questions which the personnel specialist asks of the profile are:

(1) What is the human supposed to do at any particular point in the mission?

(2) What are the operational factors to which the operator will be exposed at these points?

(3) Can the operator perform his functions adequately with regard to these operational factors?

(4) If not, what must the design configuration be in order to permit the operator to function adequately?

In segmenting the mission, the procedure is to:

(1) Divide the mission into convenient time segments, each of which has a cohesive purpose and related operations.

(2) Segments should represent times when major functions start and terminate.

(3) Segments, although normally end to end, may overlap, provided that analysis indicates a time overlap of differential groups of functions.

(4) Determine or estimate the probable durations of each time segment.

(5) Graphically arrange segments on a time scale for checking completeness.

The mission segments themselves are not useful in the design process except insofar as they help in identifying those points at which the operational environment or the mission requirements may tend to overload the operator.

TABLE XIX

SM-X MISSION SEGMENTS

Segment Start Time (in minutes)	Segment	Segment Demarcation
Variable by distance, time starts at site	Transport system equipment to launching site	Deployment order
0	Assemble missile and prepare pad	Reach site
10	Erect missile	Missile moved to pad
15	Activate and checkout missile guidance and control subsystems	Missile in launch attitude
23	Insert mission and target data	Arm and fuze test OK
Timehold Indefinite	Maintain alert status*	Warhead burst altitude set
27	Arm warhead	Arm order-redeploy order
30	Launch missile	Fuzing check complete strike order
30	Prepare for** Redeployment	Missile launched
		Trailers ready to move

* This segment is not required if missile is to be launched immediately.

** This segment is not required if missile is launched.

PRD INPUT 1C: IDENTIFY AND DESCRIBE MISSION/SYSTEM FUNCTIONS

Mission functions are those things which the system must accomplish in order that the system's performance may meet specifiable criteria. Functions are usually identified by verbs, e.g., select, transport, arm, guide. Mission functions are supposed to be independent of equipment design considerations, but the engineer typically combines his description of mission functions with the equipments he feels should implement these, and so equipment functions are derived concurrently with mission functions.

Every mission function implies an equipment and personnel function. It is the Human Factors specialist's job to identify and describe these personnel functions, since they lead directly to the specification of the personnel tasks to be performed.

Data sources for mission function identification are previous mission profile and segment data, system analysis/engineering functional data and design feasibility data concerning subsystem requirements. The procedure for determination of system functions is to examine the mission profile/segment data and to determine what continuous or long duration and discrete or short duration functions are required to implement the mission. This is essentially a judgmental process, which means that no clear cut procedural rules are available to describe it.

This activity is essential to the determination of personnel functions, but it does not of itself lead to any design recommendations which the Human Factors specialist can suggest to the engineer.

TABLE XX

SYSTEM FUNCTIONS, MISSILE SM-X

Mission Segment	System Function
Transport System Equipment to Launching Site	1. Supply automotive energy to transport a. Missile b. Warhead and nose cone c. Guidance modules and spares d. Transporter erector e. Operations trailer f. Electrical power generator trailer g. Crew quarters, mess, administrative and security trailers
	2. Control above prime movers as necessary for trip from air base to site. Communications equipment and procedures required for communicating among vehicles during move. Will status of missile and warhead have to be monitored during move? If so, how will movement of vehicles affect monitoring displays? What must and and can be monitored during move?
Assemble Missile and Prepare Pad	1. Transport W/H, nose cone, and guidance modules to missile
	2. Mate components. Mating equipment required. Implications for weights to be lifted by personnel.
	3. Attach components and physical links. Stress importance of identifying components for fast assembly.
	4. Lay portable pad support for missile.
Erect Missile	1. Control angular movement of missile from horizontal to vertical position.
	2. Secure missile on pad.

TABLE XX

SYSTEM FUNCTIONS, MISSILE SM-X

Mission Segment	System Function
Activate and check out missile guidance and control subsystems	1. Activate gyros and other components 2. Activate test instruments 3. Check yaw accuracy 4. Check roll accuracy 5. Check pitch accuracy 6. Identify, remove and replace malfunctioning units 7. Communicate possible no-go situation to launch trailer 8. Test warhead arming and fuzing components
Insert mission and target data	1. Orient missile in azimuth 2. Insert trajectory tape 3. Set warhead burst altitude (bombardment mission)
Maintain alert status*	1. Periodically monitor all loops for in-tolerance functioning 2. Provide warning when malfunction exists 3. Isolate out-of-tolerance condition to specific module. Because of requirement for fast reaction, malfunction diagnosis will have to be highly automated. 4. Remove and replace module 5. Report existing and anticipated missile out-of-commission time.
Arm warhead upon receipt of strike order	1. Arm warhead. Safety precautions. 2. Recheck fuzing system.

* This function is not required if missile is to be launched immediately.

TABLE XX (concluded)

SYSTEM FUNCTIONS, MISSILE SM-X

Mission Segment	System Function
Launch missile upon receipt of strike order	1. Make final subsystem checks (probably all automatic).
	2. Activate firing circuit.
	3. Clear launch area.
	4. Ignite engine.
Prepare for site redeployment ** upon receipt of order	1. Remove missile from pad to TV
	2. Disassemble missile, nose cone and guidance.
	3. Load nose cone, guidance, and spares in helicopters.
	4. Disassemble and stow launch pad.
	5. Ready all trailers for movement.

** This function is not required if missile is launched.

PRD INPUT 1D: DETERMINATION AND DESCRIPTION OF FUNCTIONS TO BE PERFORMED BY SYSTEM PERSONNEL

In an ideal sense, this activity involves the allocation of responsibility between equipment and personnel for the implementation of the function. Supposedly, this is performed on the basis of determining for which functions equipment can perform in a manner superior to personnel and vice versa.

In actual practice, the nature of the system often determines that major (top-level) functions be performed either by machines or by men, and no conscious allocation of responsibility is required. For example, a human cannot replace a jet engine as the power plant for a fighter. On the other hand, the fighter cannot be unmanned (or else it becomes a missile).

At the subfunction level, however, there may be alternative ways of performing the subfunction and here tradeoffs are possible (see Tables XXI and XXII). Thus, a question might arise as to whether bombing should be performed automatically by radar or by a bombadier using an optical sight (or by both, with one backing up the other). This question might have to be answered in terms of the accuracy required in the bomb run as compared with the accuracy capable of being achieved by the human, as well as other cost, weight, etc., factors involved in the installation of an automatic bombing system. In such tradeoff situations, the Human Factors specialist will input data concerning known human capabilities and limitations.

The formal methods reported by Rabideau and Bates (1962) which describe how one allocates functions between equipment and personnel are largely unused in the actual design situation. The engineer in almost all cases (given equivalent cost, equal ability to perform the function, etc.), would prefer that a function be performed automatically. Certain off-the-shelf hardware impose particular personnel functions. In any case, the length of time available for making decisions of this sort is not unlimited (as seen in the present study) and all the formal methods are overly complex.

The personnel specialist can do two things in this phase of the analysis:

(1) He can point out to the engineer functions which require, because of their special demands, human implementation. Among these demands are complex decision-making, precise perceptual discriminations, etc. He can list these special requirements and suggest their implications for design.

(2) He can review the functional allocations made implicitly by the engineer to determine whether the functions allocated to personnel will:

(a) stress the operator and, therefore, lead to inefficiency

(b) require special kinds of equipment to permit the implementation of the function by personnel

From the engineer's standpoint, this kind of personnel analysis will suggest where special kinds of equipment are required to assist the human in performance of his functions or where, perhaps, it might be advisable to replace a potentially weak human link with an equipment.

TABLE XXI

ALTERNATIVE WAYS OF CHECKING GUIDANCE AND CONTROL LOOPS - MISSILE SM-X

Alternative 1 Function Description	Alternative 2 Function Description	Alternative 3 Function Description	Alternative 4 Function Description
Technician at missile with portable test equipment initiates inputs and checks and records outputs. If equipment is out of tolerance, he diagnoses fault and repairs.	Technician at missile connects cabling on orders of operator at console. Operator initiates input and checks and records output. If equipment is out of tolerance, technician traces fault using operator communicated outputs to diagnose. Technician then repairs.	Technician at missile connects cabling. Operator starts console sequence. Operator monitors console for red light indication. If red light flashes, technician and operator use machine information to diagnose fault. Machine records all outputs.	Sequence is part of automatic total missile checkout sequence. Operator receives audible no-go signal and red light indicates malfunctioning unit. Operator communicates to technician which unit to replace. Machine records all cutputs.

TABLE XXII

FACTORS TO BE CONSIDERED IN TRADING OFF ALTERNATIVE WAYS OF CHECKING GUIDANCE AND CONTROL LOOPS

Alternative 1 Function Description	Alternative 2 Function Description	Alternative 3 Function Description	Alternative 4 Function Description
<u>Type of output</u> Information display Portable voltmeter Pointer indicator	<u>Type of output</u> Information display Panel voltmeter Digital	<u>Type of output</u> Information display Panel light	<u>Type of output</u> Information display Panel light & signal Malfunctioning unit displayed
<u>Cost</u> Low fabrication Low instrumentation	<u>Cost</u> Medium fabrication Medium fabrication	<u>Cost</u> High instrumentation High fabrication	<u>Cost</u> Very high instrumentation Very high fabrication
<u>Time</u> Short to achieve design Long to operate	<u>Time</u> Longer to achieve design Shorter to operate	<u>Time</u> Long to achieve design Short to operate	<u>Time</u> Very long to achieve design Very short to operate
<u>Skill level</u> Fairly high (Man must test and repair)	<u>Skill level</u> Operator-fairly low Maintenance-fairly high (Must diagnose)	<u>Skill level</u> Operator-medium Maintenance-low (Remove-replace)	<u>Skill level</u> Operator-low Maintenance-low (Remove-replace) (Machine diagnoses fault)
<u>Manning</u> Possible for one man to test and maintain	<u>Manning</u> Two men needed Communication needed	<u>Manning</u> Two men needed Communication needed	<u>Manning</u> Two men needed Both can assume other duties at same time-needed only when equipment malfunctions
<u>Accuracy</u> Possibility of misreading meter especially if meter must be read to close limits	<u>Accuracy</u> Likelihood of misreading small	<u>Accuracy</u> Dependent on equipment reliability	<u>Accuracy</u> Dependent on equipment reliability, error probability on part of operator practically zero

TABLE XXII (continued)

EFFECT OF ENVIRONMENTAL CHARACTERISTICS ON ALTERNATIVE WAYS OF CHECKING GUIDANCE AND CONTROL LOOPS

Alternative 1 Function Description	Alternative 2 Function Description	Alternative 3 Function Description	Alternative 4 Function Description
Geography	Geography	Geography	Geography
Mobility requirement precludes permanent missile cover. Canvas shelter only to be allowed	Mobility requirement precludes permanent missile cover. Canvas shelter only to be allowed	Mobility requirement precludes permanent missile cover. Canvas shelter only to be allowed	Mobility requirement may seriously impair the space needed for the equipment needed to automate
Weather	Weather	Weather	Weather
All weather arctic operational requirement limits likelihood of technician remaining long under canvas shelter only	All weather arctic operational requirement limits likelihood of technician remaining long under canvas shelter only	Operator could check from van technician. Would only be required outside for short periods in case of malfunction	Technician would only be outside for time to remove and replace diagnosed unit
Wind	Wind	Wind	Wind
45 mph wind could endanger man on missile. Test equipment could easily be lost	45 mph wind could endanger man on missile	Technician would be exposed to wind for short periods only. Would not need too much freedom of movement, hence could be lashed if necessary in high wind	Minimum exposure time for technician; very little mobility needed for him

TABLE XXII (continued)

SUMMARY OF MAN-MACHINE FUNCTION TRADEOFFS FOR MISSILE SM-X

Start Time (from initial function)	Function	Man-machine Combination	Start Function Cue	Start Action Required	Remarks
T = 15 min. (duration 2 min.)	Activate gyros and other components	Human initiated	Completion of secure missile	Manually operated switch	Action well within human capabilities. No unreasonable time pressure. Environmental program likely to demand function be performed indoors. (therefore remotely)
T = 15 min. (duration 2 min.)	Activate test instruments	Human initiated	Completion of secure missile	Manually operated switch	Action well within human capabilities. No unreasonable time pressure. Environmental program likely to demand function be performed indoors. (Therefore remotely)
T = 17 min. (duration 2 min.)	Check Yaw accuracy	Machine Check Human Monitor	Circuit Warm up complete. (Either machine indicated or automatic sequence)	Either manually operated switch or automatic program	Two minute time duration for operation. Precludes use of human from time stress standpoint. Automatic operation should include no-go indication to human
T = 19 min. (duration 2 min.)	Check roll accuracy	Machine check human monitor	Yaw accuracy checked (automatically sequenced)	Automatic program	Two minute time duration for operation. Precludes use of human from time stress standpoint. Automatic operation should include no-go indication to human

TABLE XXII (continued)

Start Time (from initial function)	Function	Man-Machine Combination	Start Function Cue	Start Action Required	Remarks
T = 21 min. (duration 2 min.)	Check pitch accuracy	Machine check human monitor	Roll accuracy checked. Automatically sequenced)	Automatic program	Two minute time duration for operation. Precludes use of human from time stress standpoint. Automatic operation should include no-go indication to human
T = 18 min. (duration 2 min.)	Test warhead arming and fuzing components	Machine check human monitor	(automatically sequenced)	Automatic program	Two minute duration for operation. Precludes use of human from time stress standpoint. Automatic operation should include no-go indication to human
T = 16 min. (duration thru segment)	Identify, remove, replace malfunctioning units	Identify machine indicated. Remove, replace	Machine indicates malfunctioning	Malfunction indication	Time stress precludes human identification of malfunction. Machine to remove, replace is uneconomical compared to human. Logistics must be well organized to allow human to perform, remove, replace
T = 15 min. (duration-thru segment)	Communicate no-go situations to launch trailer	Human operation communication equipment	Human recognizes malfunction cannot be corrected within time tolerances for function	Initiate communication (audio)	Decision factors are ambiguous. Programming all factors into machine for machine decision would be prohibitive

TABLE XXIII

SAMPLE TASK TIME BASE LAYOUT FOR

SM-X MISSILE SYSTEM "ASSEMBLE MISSILE" MISSION SEGMENT

Function/Task	0	2	4	6	8	10
A. Transport W/H etc.						
1. Attach sling to nose cone						
2. Position crane (truck mounted)						
3. Attach sling to hook						
4. Hoist nose cone to clear truck bed						
5. Rotate nose cone forward						
6. Position truck ahead of transporter-erector						
B. Mate missile and nose cone						
1. Use crane and truck to mate components						
C. Attach nose cone to missile						
1. Install bolts to attach components						
D. Lay pad						
1. Carry sections from T-E to pad area						
2. Assemble sections to form pad						

PRD INPUT 1E: DESCRIPTION OF THE INTERRELATIONSHIPS OF PERSONNEL FUNCTIONS

Once the personnel functions have been specified, it is necessary to describe how they interrelate. The personnel functions which were determined in the previous analytic step are now assigned to the individual stages of the mission as described in the mission profile. Particularly where that profile has a time base, this permits one to specify the sequence in which personnel functions should be performed (see Table XIII). The result can be described graphically in the form of a time-line analysis and personnel functional flow diagrams (see PRD Input 2C).

There are no specific design applications of this analytic step, primarily because the function level (even that of the sub-function) is still too gross to do more than describe the personnel aspect of the system in very general terms. However, it will permit the personnel specialist to check the allocation of functional responsibilities to system personnel, to insure that too many functions have not been assigned at particular stages of the mission to personnel. The time-line analysis which will be derived as a function of the task analysis (PRD Input 2) is also an essential step in the derivation of the required number of system personnel.

PRD INPUT 2: TASK ANALYSIS

Task analysis is the primary method for developing all subsequent PRD inputs. It follows immediately upon performance of the mission/event analysis. The outputs of the task analysis, in as detailed a format as possible, should be available as inputs to the PTDP, and should be pregressively refined and made more detailed in the RFP and SOW. More detailed task analyses can be performed after design is initiated, but in general, such analyses should lead or at least be concurrent with the equipment for which the analyses are begun.

Task analysis outputs are as complete a description as possible of how the operators and maintenance personnel in the system will function. From the task analysis implications may be drawn for personnel requirements, such as number of personnel, skill level, job positions, etc., all of which have major design implications (which will be discussed in connection with the individual task analytic output).

Task analysis outputs include the following:

(1) Lists of tasks

(2) Task descriptions

(3) Task sequence

(4) Task criticality

(5) Task duration

(6) Task difficulty/error likelihood

(7) Time-line analysis

(8) Position descriptions

A task is a complex of behaviors (perceptual discriminations, motor responses, decisions and analyses) which are related to each other in terms of time, immediate purpose and a common man-machine output.

The procedure for identifying tasks is to list the functions to be performed by personnel (see PRD Input 1D). These may be whole functions or functional elements performed wholly or partially by the human, in which the human initiates some action or the action is directed at the human or in which the operator is a communicator or controller of a machine function. For example, the following might be functions: "Drive tank, navigate to IP point; diagnose malfunctions."

The tasks and their functional elements, i.e., sub-tasks, should be identified and labeled. The task is some activity which implements the overall function described above, as, "Activate engine; plot position, etc." Sub-tasks in their turn implement tasks, e.g., "Advance throttle, turn steering wheel, engage clutch, etc." Ordinarily the task should involve the output of only one man in interaction with a machine component. Task and sub-task labels should start with verbs which indicate the nature of the activity being performed.

The results of this procedure will be the list of tasks. To secure task descriptions in additional detail, it will be necessary to analyze the individual tasks to specify the following:

(1) Equipment or personnel inputs which initiate the performance of the task, e.g., flashing indicator, verbal message

(2) The behavior involved in task performance, e.g., activation of the throttle, reading of a meter

(3) Outputs which result from the performance of the task, e.g., lever is activated, toggle switch is thrown

(4) Feedback available to the operator from task performance which may lead to next task in sequence, e.g., verbal message of confirmation, indicator light illuminates

(5) Estimation of task duration

Tasks are then grouped into positions. A position is a combination of tasks bound by similarity of task characteristics, physical location of task performance, internal sequence of operations and imposed skill demands so as to form a natural work procedure for one man. The grouping of tasks into positions helps to determine how many men will be required and approximately what the individual skill requirements will be.

Tasks are grouped into positions by performing the following steps:

(1) Lay out tasks on a time base. Estimates of task duration are combined with data concerning the time phasing of the tasks within a mission segment.

(2) Estimate task skill demands on the basis of decision and perceptual/motor requirements levied by the task and the operational environment on the operator.

(3) Arrange tasks according to tentative positions. This is "cut and try" procedure. The attempt is made to reduce "idle" time (men not being productively employed) to a minimum.

The task analysis itself is a methodology. The personnel specialist is concerned with communicating only the outputs of the analysis to the engineer, not the methodology itself, which is of interest only to the specialist.

PRD INPUT 2A: LISTS OF TASKS

In this and in subsequent descriptions of PRD inputs resulting from the task analysis, only the design implications of the input will be discussed, since the procedure for developing the input has already been described.

An example of a task list is provided in Session 1 of Appendix I. Note that the task list provides only the barest amount of information to the engineer and should be supplemented with other task analytic outputs, such as task descriptions, task criticality evaluations, etc.

As a minimum, the task list should be included as a basic input to the PTDP, but in order to fully satisfy the personnel section of that document, it should be supplemented with other task information.

The engineer is likely to view the task list as comparable to an operating procedure or as a beginning step to the development of an operating procedure. This is useful in itself, because it causes him to think about the operational uses of equipment in terms other than equipment functioning. As described previously, the engineer seems temperamentally loathe to think in operational terms, a form of analysis which is required for incorporation of personnel considerations in design.

The task list may suggest to the engineer that certain types of control-display equipment are needed to permit implementation of the tasks. For example, if the task is to control the amount of pressure in a vehicle, it is obvious some type of control equipment with meters or other displays will be required. Since this deduction is relatively simple, it is likely that the engineer will make the same deduction also. However, because of his personnel orientation, the specialist may be able to read more into the task than that, particularly if the task is described in detail. To the extent that the task list is detailed, it will help suggest the general system configuration needed to permit implementation of these tasks.

In presenting the information to the design engineer, the Human Factors specialist should not leave it to the engineer to draw his own implications from the data but should recommend whatever design implications the input suggests to him. This is a general principle which applies to all PRD inputs. The system description in the PTDP should, of course, incorporate all the personnel specialist's concepts concerning system design (those which have survived compromise with the system engineer).

PRD INPUT 2B: TASK DESCRIPTIONS

The task description is a more detailed description of the task listed in Input 2A. Preliminary task descriptions should be available as an input to the PTDP and more detailed task descriptions in the RFP/SOW. However, it is unnecessary and unwise to present to the engineer all the behavioral details with which the personnel specialist would describe the task. Indeed, in line with what has been learned in the present study, it is preferable to describe all tasks in terms linked as closely as possible to system operations.

Highly detailed task descriptive information should be extracted and presented in the PTDP only when a particular task is significant for design because:

(1) It has a high probability of error

(2) It has special skill or knowledge demands

(3) It is especially critical to system performance (see Input 2D).

With regard to design implications, highly critical tasks or those with a high probability of error may require that special provisions be made to accommodate these tasks in the design of the equipment with which the task may require guarding. A special procedure or special feedback indications may have to be developed for such a task. Interlocks, where applicable, may have to be designed.

If skill requirements for a particular task are excessive, the procedure and equipment imposing these demands may have to be modified, e.g., breaking up one complex task into two simpler ones. A change in procedure may involve a change in equipment design; from that standpoint procedural changes can be considered part of design modifications. Performance aids may be another solution. The point is that the task description may indicate a potential problem area which, when brought to the engineer's attention, may result in a design modification.

Table XXIV presents task and sub-task descriptions for one segment of the SM-X mission.

TABLE XXIV

HUMAN FUNCTIONAL ELEMENTS, TASK AND SUBTASKS FOR ACTIVATION AND CHECKOUT OF GUIDANCE AND CONTROL SUBSYSTEM

Function	Human Functional Element	Task	Sub-task
Activate Gyros and other components	Make Power "ON" Input	1. Turn on AC and DC missile guidance power	a. Check to assure that all circuit breakers are "IN" b. Position AC missile power guidance switch at "ON" c. Position DC missile guidance power switch at "ON"
Activate Test Instruments	Make Power "ON" Input	2. Turn on missile preflight analyzer power	a. Check to assure that test patchboard is inserted and locked b. Position analyzer master power switch at "ON" c. Insert Test tape in tape reader and lock in place
	Make analyzer self test initiating input	3. Start analyzer self-test test sequence	a. Position test switch at "SELF-TEST"
	Monitor self-test readout		b. Check test result window for indication of analyzer self-test result
	Provide corrective inputs and monitoring when self-test yields a "NO-GO"	3 A. (Alternative procedure) isolate and replace malfunctioning analyzer module	a. Check code displayed in malfunctioning module window against modular code table b. Remove module from analyzer and take to storage

TABLE XXIV (concluded)

Function	Human Functional Element	Task	Sub-task
Activate Test Instruments (concluded)			c. Obtain replacement module from storage, take to analyzer and insert it
			d. Repeat Task 3
Check Yaw (Roll) (Pitch) Accuracy	Make gyro test initiating input	4. Start and monitor gyro test program	a. Position test switch at "MISSILE TEST"
	Monitor test results readout		b. Check test result window for "GO/NO-GO" indication. Analyzer automatically performs test sequence
	Provide corrective inputs and monitoring when gyro test yields a "NO-GO"	4.A. This is virtually a repetition of 3A, excepting that a second technician is required to remove and replace modules at missile	

PRD INPUT 2C: TASK SEQUENCE

Task sequences should be displayed in the form of a personnel functional flow diagram, examples of which are presented in Figures 4 and 5 in Appendix I. Note that the diagram will indicate major decision points which may impose skill demands on the operator.

The personnel functional flow diagram, the purpose of which is to show the interrelationships among tasks, should be available to the engineer at the same time the latter is developing his equipment flow diagrams. The diagrams should also be included as part of the PTDP.

The interrelationship of tasks may suggest to the engineer certain logical groupings of functions within particular equipments, e.g., certain task/function groupings which are related might be incorporated in one set of control equipment, whereas another grouping might be implemented by another group, etc. The interrelationships may also suggest the necessity for communications equipment. Task sequence data will also be useful in developing preliminary "top level" system operating procedures which, in turn, will structure the overall system equipment configuration. The grouping of tasks will help to suggest job positions.

The Human Factors specialist can use the personnel functional flow diagram as a means of checking on the adequacy of the system configuration by comparing diagrammed personnel events with corresponding diagrams of equipment events. A one-to-one correlation must exist between any personnel function/task and its corresponding equipment function/task. Asynchrony will indicate that the equipment or the task must be modified. Past experience suggests that in initial design the engineer may overlook the necessity for supplying equipment to implement personnel task requirements.

PRD INPUT 2D: TASK CRITICALITY

This is not an independent output, but one which is a deduction from the nature of the task and is presented to the engineer with the task description in form of a note to the task description.

There are three major steps in the derivation of task criticality:

(1) Identify the potential errors which can be made in performance of the task. This is largely a matter of considering the elements of the task and the perceptual, motor and decision-making demands imposed on the operator. Thus, in a simple case of a task which involves (a) reading a pressure guage regulating the internal pressure of a rocket and (b) stopping a pump at a specified pressure, errors may manifest themselves in two ways:

(a) failing to stop at the prescribed point

(b) stopping the pump before the prescribed point

(2) Identify the effect of each potential error on system operation.

Thus, in the example above, failing to stop the pump at the prescribed point may result in overpressurization and bursting of the rocket being pressurized. Stopping before the prescribed point will result in underpressurization, so that certain sensitive instruments requiring a pressurized atmosphere will function erratically.

(3) Estimate the relative criticality of the potential errors. Criticality may be scaled in terms of categories such as, loss of personnel, destruction of the system, mission failure or abort, mission degradation, mission delay, etc. In these terms, overpressurization may be more critical than underpressurization, since it may result in explosion of the rocket and destruction of the rocket and launch pad as well as loss of life, while underpressurization is less critical, since the mission may (not certainly, but may) be degraded.

Pointing out a task as being critical to the engineer "flags" that task as one requiring special consideration in design. Among the solutions which are possible (certainly the list is not exhaustive) are:

(1) Replacing the human by an automatic means of accomplishing the function if the desired level of correct performance cannot be achieved in any other way

(2) Providing means to reduce the probability of error, e.g., assigning a special feedback device to warn the operator when the task is being performed incorrectly

(3) Assigning the task to only highly skilled personnel

Task criticality is highly related to specification of task difficulty/error likelihood. Since the engineer thinks in terms of physical effects on the system, it is preferable to flag the task as being critical without indicating that it also has a high difficulty/error likelihood index. The provision of quantitative indices of a highly precise nature, such as probability of operator error to four figures (e.g., .0013) is not advised, since the engineer cannot interpret the quantitative values in design-relevant terms. A gross categorization of task difficulty, such as a three-part scale:

1. simple, routine

2. somewhat difficult

3. very difficult

is as much precision as the engineer can handle in design terms. Moreover, it is unnecessary to apply the above scale to each task, but only to those few, very critical ones which merit design attention.

PRD INPUT 2E: TASK DURATION

Task duration should be considered in two ways:

(1) as a system requirement, i.e., the time within which the task must be performed in order to accomplish a given system function

(2) as an anticipated human performance capability, i.e., the time within which the operator can actually perform the task.

Item (1) above is a criterion against which Item (2) can be evaluated as satisfying or failing to satisfy system time requirements.

As a system requirement, a task may have to be accomplished in so short a time period that the operator either cannot physically perform the task in that time or the probability of his making an error will be substantially increased because of the time-loading. In either case, special attention must be drawn to such a task. If the system time requirement is inflexible, it may be necessary to automate the function involved (to eliminate the operator), or else to redesign the manner in which the task can be performed or the equipment to be operated or maintained.

Task duration is, of course, not critical unless the system's required response time is also critical to the successful accomplishment of the mission. Hence, it is necessary to analyze the mission segment in terms of its time demands before examining any individual task duration. Information required in order to perform task duration analysis will include:

(1) system performance time requirements

(2) description of the tasks to be performed by personnel in each mission segment

(3) estimated time required to perform the task

Of these informational requirements, the most difficult to secure is (3) because it requires data on the performance time capability of personnel (e.g., hooking up an umbilical connection usually takes ______ time). That information can be secured from previous comparable systems in which similar or identical tasks have been timed, or from the body of general human performance data in the literature. Neither of these two sources is especially available.

The following information should be set down by the Human Factors specialist for each task:

(1) The time in minutes from the start of a mission segment, at which a given output is required. This may also be expressed as a tolerance range, "not earlier than," "not later than"...

(2) The time duration of the task in minutes

(3) The maximum time permitted by system requirements for the task to be accomplished

(4) Notes as to whether a given task is self-paced, machine-paced or paced by other task requirements. These notes may suggest the manner in which a redesign of the task is possible.

Task duration data also serve as inputs to the development of time line analysis (PRD Input 2G) and, hence, are useful in the determination of job positions.

Table XXV is an illustration of a task duration analysis for the "assemble missile" segment of SM-X operations.

TABLE XXV

TASK DURATION ANALYSIS FOR SM-X "ASSEMBLE MISSILE" SEGMENT

Function/Task	Output: Not earlier than	Output: Not later than	Duration	Input: Earliest	Input: Latest	Remarks
A. Transport W/H etc.						
2. Position crane	--	T + 1	1 min.	--	T + 0	(1) Output cannot be made earlier than time missile clears track bed
5. Rotate nose cone, forward	(1)	T + 3	1	T + 2 (2)	T+2.5	
6. Position truck ahead of transporter erector	T+3	T + 4	1	T+2.5	T+3	(2) Time of initiation depends upon rate at which a second technician hoists nose cone
B. Mate missile and nose cone						
1. Use crane & truck to mate components	--	T+6	2	T+3.5	T+4.5	(3) Output can start as soon as components are mated
C. Attach nose cone to missile						
1. Install bolts to attach components	(3)	T+10	4 (4)	T+5.5	T+7	(4) This task is also performed by a second technician, who exerts a pacing effect

PRD INPUT 2F: TASK DIFFICULTY/ERROR LIKELIHOOD

The Human Factors specialist is especially concerned about task difficulty because this, in turn, may lead to a higher error probability with its attendant effects on mission accomplishment. Task difficulty arises because system requirements are incompatible with and overload the skill capability of the manpower assigned to perform the task.

Task difficulty is not the same as error likelihood. A difficult task need not automatically have a higher error probability, if personnel of higher skill are available to compensate for the increased task difficulty. The significance of task difficulty is intensified when the task is also critical to the accomplishment of the mission. Such difficult-critical tasks automatically demand redesign because their attendant error probability cannot be accepted. As in the case of maximum task durations, which the operator's performance cannot meet, it may be necessary to automate the performance of the task, relax the accuracy requirement (thus implicitly accepting a higher error probability) or redesign the task to simplify it.

The determination of task difficulty must be made by analyzing the individual task in terms of the inputs which initiate the task (e.g., verbal message) and the outputs which accomplish the task (e.g., switch action). The Human Factors specialist will look for the following characteristics which may (not necessarily will) indicate an excessively difficult task:

(1) The input which initiates task requires excessively precise visual discriminations or fine motor responses

(2) The operator's response to the initiating inputs must be performed so quickly that he has problems in keeping up with the initiating inputs

(3) The accuracy demanded of the operator in responding to the initiating inputs is excessive (e.g., heading error must be within 0.5 degrees)

(4) The task must be coordinated extremely precisely with other tasks performed by other personnel

(5) The environment in which the task must be performed tends to degrade task performance (e.g., high noise levels, acceleration).

(6) Information from multiple sources (e.g., several displays, on a control panel) must be integrated by the operator in order to make a decision

(7) The amount of information available on the basis of which a decision must be made or an action taken is less than desirable

(8) The task is composed of many sub-task elements, the correct performance of all of which is necessary to task performance, but the amount of feedback provided (knowledge of correctness or incorrectness of sub-task accomplishment) is inadequate

(9) Short-term memory requirements for task performance are excessive (e.g., memory for long sequences of target coordinates)

The design solutions available for reducing task difficulty include:

(1) Additional training provided or selection of higher skilled personnel

(2) Simplification of the task by such means as combining information sources, providing additional feedback, subdividing the task among several operators, changing the manner in which the task must be performed, etc.

(3) Reducing system requirements by accepting a higher error probability, longer response time, etc.

The task analysis provided to subjects of this study in Session 4 (Appendix I) contains sample difficulty levels which, when applicable, should be included in task descriptions in the PTDP, RFP and SOW.

Error likelihood has been discussed in connection with PRD Input 2D (Task Criticality).

PRD INPUT 2G: TIME-LINE ANALYSIS

The time-line analysis (TLA) presents major functions and/or tasks (depending on the level of analytic detail included in the TLA) in terms of the time required to perform the functions/tasks and the combination of personnel necessary to successfully complete the functional requirements of the system. Figures 9 and 10 of Appendix I present examples of the TLA.

A TLA for major (top-level) functions must be available as part of the backup data for the system description in the PTDP. A TLA for major tasks must be part of the backup data presented as part of the RFP/SOW.

The TLA provides more detailed task sequencing and interrelationship data than the personnel functional flow diagram (although the latter has its own uses and should not be replaced by the former). The TLA may have implications for design when, for example, the analysis indicates that workplace configuration must be considered to accommodate several people working in the same area; or where communications or other signaling equipment may be required for interaction among personnel.

The TLA may indicate points in the mission sequence where the timing of events is so critical that the ability of the operator to respond quickly enough may impose a delay which could jeopardize mission success; consequently, the operational sequence may have to be modified or the means of implementing the sequence may have to be automatized. All of this is in addition to its other primary function in helping to indicate the number of personnel required, which also has its impact upon design.

PRD INPUT 2H: POSITION DESCRIPTIONS

The position description describes the functions and tasks to be performed by each category of personnel to be assigned to the system crew. It is a summary of the available information concerning what must be performed by the individual in the individual job position.

A major element in the position description will, therefore, be the task lists and descriptions described previously. Skill requirements for the position and the training to be provided to the individual performing the job should also be noted. The maximum number of personnel who will fill that job position should also be indicated.

Preliminary job descriptions should be available in the PTDP and more detailed descriptions should be provided in the RFP/SOW, although many of the elements of the information will be available earlier than at these times, of course.

The design implications to be inferred from the position description are those which have been described earlier as being implied by the task data, e.g., lists of tasks, characteristics of those tasks and task interrelationships. Beyond this the position description does not have a major potential impact upon the system configuration.

PRD INPUT 3: NUMBER OF PERSONNEL PERMITTED

The number of personnel permitted in the operational crew described in terms of individual job positions, (e.g., three radar maintenance mechanics), should be made available to the design engineer in the PTDP. This is phrased as a requirement, not as a recommendation, although it will probably be the result of a compromise with the system engineer.

The number of personnel specified must be a maximum, for two reasons: First, one wishes to have no more than the minimum number of personnel needed to do the job; second, a maximum (not to be exceeded) figure acts as a constraint on the designer by implying that any design concept requiring the services of additional personnel will not be satisfactory. A minimum figure (i.e., at least this number of personnel will be required) will not act as a design constraint, since with a minimum, the engineer is permitted to design for any upper limit he wishes.

The following is an example of an acceptable personnel requirement: "The contractor shall design and develop the propellant transfer subsystem for operation and maintenance by a maximum of six Air Force personnel (1 Fuel Supply Officer, 2 Fuel Specialist/supervisors, 3 Liquid Fuel Systems Maintenance Specialist/Technicians). Design documentation shall be provided to verify that the subsystem can be operated and maintained by this manning structure."

This input (number of personnel) is derived from the task analysis and time-line analysis. Determining the number and type of tasks and their distribution over time (overlap of operations) indicates the number of personnel needed.

The total number of personnel permitted directly affects the amount of automation required. With a certain minimum number of personnel recourse must be had to automatization (this is, of course, not the only or even the primary reason why one automates, but number of personnel can be a significant factor in automation). Obviously, certain functions cannot be performed by personnel when the number of personnel is reduced beyond what the engineer considers a minimum for manual operation. It is unnecessary for the personnel specialist to make specific design recommendations when he imposes this requirement, but he must be aware of its design consequences (and in any event the engineer will make him aware of them). Therefore, this requirement should not be imposed lightly.

Design Implications

(1) For automation. Certain system functions cannot be performed with a given number of personnel without automatizing these functions. If the number of personnel is small enough, complete automation may be necessary. Once automation is accepted in principle, many design modifications specific to individual equipments may result.

(2) For system operating procedures. A smaller number of personnel may require that functions be performed serially rather than concurrently, which means that overall mission time may be stretched out.

PRD INPUT 4: SKILL LEVEL DESCRIPTIONS

This information should be provided in at least general form in the PTDP, and in specific detailed form in the RFP/SOW. The determination of skill level and the provision of this information following the start of design is of little value to the system engineer.

An adequate definition of skill level is extremely difficult to provide. Its behavioral dimensions are quite obscure. Consequently, the design engineer has great difficulty in understanding the implications of this parameter.

Two types of skill level descriptions exist:

(1) Skill required by the task

(2) Skill expected to be made available as a result of training or selection. The former is what is referred to commonly as the skill level description. The latter is actually proficiency. For optimal system performance, the two levels should exactly balance out in the completed system.

Skill level appears to contain the following dimensions which are inversely related to the amount of skill required:

(1) Amount of supervision required (least and most)

   (a) Highest skill level is represented by the operator's ability to perform all tasks (critical or not) without supervision

   (b) Performance of all critical tasks under supervision; all other tasks performed without supervision

   (c) Performance of major tasks under supervision; all routine tasks performed without supervision

   (d) All tasks must be performed under supervision

(2) Error probability; high error probability indicates that the task demands high skill

(3) Need for performance aids, e.g., checklists

(4) Slow response time by the operator

(5) Task demands imposed upon the operator. These demands may be scaled on a continuum of decision and/or perceptual-motor complexity, e.g., more complex decisions in the task require higher skill level

The skill level description should be phrased in terms of the specific tasks to be performed by personnel in operating the system to be designed. Hence, the adequacy of the skill level description is partially dependent on the detail in the task description:

A sample skill level requirement might be phrased as follows: "Hardware design shall be accommodated to the following skill level requirements. The skill level of the five-level fuel maintenance specialist to be assigned to the __________ system will permit him to perform the following tasks without supervision:

(1) Capable of hooking up flex hoses connecting railroad cars to the ground supply area

(2) Opening and closing manual hand valves in accordance with written checklists

(3) Monitoring propellant flow

(4) Visual inspections of piping ("leak checks")

Under supervision to perform:

(1) Calibration of flow meters and associated instrumentation

(2) Purge and drain propellant lines

The five level fuel maintenance specialist is not qualified to perform any troubleshooting or diagnostic maintenance tasks."

Skill level does not have (presently because of lack of appropriate research) direct design implications. In other words, one cannot directly convert a given skill level into a particular set of design characteristics. However, the following should be pointed out to the engineer:

(1) A high skill requirement and/or a low level of expected skill requires the provision of greater positive feedback, more interlocks (if applicable), fewer combined displays, relatively invariant and slower procedures, more checks to verify progress, etc.

(2) As related to number of personnel, a lower skill level expected may require additional personnel backup, but this has not yet been demonstrated

PRD INPUT 5: TRAINING

The training requirement specifies:

(1) Length of time training will be provided

(2) Type of training, e.g., for particular job positions

(3) Degree of proficiency to be achieved after training, phrased as an expected or available skill level

This information should be provided in preliminary form as a firm system requirement to the engineer in the PTDP and further refined in the RFP/SOW. Once equipment design has begun, this information is of no value to the design engineer.

The type of training and particularly the expected proficiency level should be specified in terms of the same system operations used as part of the skill level description. Definition of the type of training to be provided in terms of functions only is not satisfactory.

Training has design implications only in terms of proficiency (achieved skill level). The design implications are the same as those of skill level.

PRD INPUT 6: PERSONNEL AVAILABILITY

This input refers to knowledge of those personnel already in the Air Force inventory who, upon the deactivation of a system similar to the one being developed, will become available to man the new system.

This information is needed by the Air Force as one of its tradeoff criteria for the specification of skill levels to be included in the RFP and SOW. If highly skilled personnel in particular job categories become available in time to man the new system, the procuring agency will be able to specify as a design requirement to the contractor that the system should be designed to that particular skill level in these categories. The nonavailability of personnel with the particular capabilities required by the new system may or may not cause the procuring agency to require that system to be designed for relatively unskilled personnel (depending on the amount of training it is prepared to provide inexperienced personnel).

In this way, personnel availability aids in the specification of manpower requirements. The design engineer is, of course, primarily interested in the specification of the manpower needed by the new system (quite apart from their availability in inventory) but the description of the kinds of personnel who will be available to him (e.g., maintenance mechanic, four years experience/such and such a system) will give him a clearer picture of whom he should design for. The absence of a personnel availability statement will not, however, necessarily reduce design effectiveness, if the new system's manpower requirements (regardless of personnel availability) are described in detail.

Before determining personnel availability, it is necessary for the procuring agency to know in advance what job positions must be filled for the new system. This information is derived from the preceding function/task analyses. Using these job positions as criteria, it can then examine personnel in its inventory projected over system development time to determine the types of AFSCs which will become available to match the new system's manpower requirements. This kind of prediction is, of course, highly risky, since experience has shown that operational systems (and the personnel they employ) do not always become obsolete and available when anticipated. Should it be possible to include a statement of personnel availability in the potential contractor's RFP, it should be in as much detail as that required by PRD Inputs 3 and 4. In particular, skill levels, amount of previous experience and amount of additional transition training to be provided should be specified in the personnel availability statement. In addition, available AFSCs should be equated with the job positions required by the new system.

PRD INPUT 7: PERSONNEL/EQUIPMENT ANALYSIS

The Personnel/Equipment Analysis (P/E A) is not a specific PRD input to the engineer. Each time the personnel specialist submits a memorandum to the engineer interpreting a PRD input in terms of its design implications or reviewing an equipment design against system personnel requirements, he is engaging in P/E A. Hence, the P/E A is not specific to any particular developmental stage or PRD input

The P/E A should contain the following elements:

(1) Statement of the personnel requirement, e.g., number of personnel, skill level, etc.

(2) The implications of the personnel requirement for design, i.e., what should be done to meet the requirement in the form of changed equipment, procedures, etc.

(3) Alternative ways of meeting the requirement

(4) Recommended design actions

(5) Review of equipment design and the relationship of that design to the personnel requirement

PRD INPUTS FOR PTDP

The following PRD inputs should be inserted into the PTDP. Note that this list includes only those inputs which are presumed to affect the system configuration.

(1) Lists of tasks

(2) Preliminary detailed task descriptions

(3) Time-line analysis

(4) Personnel functional flow diagram

(5) Preliminary position descriptions

(6) Number of personnel required (overall crew)

(7) Skill level requirements for job position categories

(8) Preliminary training requirements

Backup mission/events analytic data, e.g., mission profile and system functions, are included in the system description and in the summary of operations and maintenance requirements. The design implications of the PRD inputs will also be included in the PTDP.

Other PRD inputs which are not of specific interest to the design engineer will be included in the personnel package, e.g., training plans, training planning information.

PRD INPUTS FOR RFP/SOW

The RFP/SOW will include all PRD inputs included in the PTDP plus the following:

(1) More detailed task descriptions

(2) Designation of critical tasks

(3) Maximum number of personnel required for individual job positions

(4) Skill level descriptions keyed to individual tasks

(5) Length, type of training and proficiency achievable for each job category

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13. ABSTRACT

The purpose of this study was to determine the effect on system design of using manpower requirements (MR) and personnel resources data (PRD) as design requirements. Equipment and personnel inputs, e.g., quantity and skill level of manning and task information, were presented incrementally to six design engineers in a simulation of the Phase 1A/1B development of the Titan III propellant transfer and pressurization subsystem. Subjects were required to create a complete subsystem design, including schematics, equipment descriptions, drawings and bills of material. Cost effectiveness measures were applied to the data. It was found that manpower requirements and PRD inputs do influence the equipment configuration, but only moderately, because equipment design proceeds so rapidly that incremental PRD inputs inevitably lag design. Engineers are responsive only to inputs which are framed as design requirements and which can be interpreted in design-relevant terms. Engineers were found to be generally indifferent to personnel considerations. The results of the study indicate that if personnel factors are to be incorporated into design, it is necessary to supply PRD inputs as design requirements to the engineer in his initial statement of work. The analyses upon which MR and PRD inputs are based must be performed prior to the issuance of a Request for Proposal and not delegated to a development contractor.

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